Studies of Alternatives to Neutrino Oscillation using Super-K Atmospheric Neutrino Data

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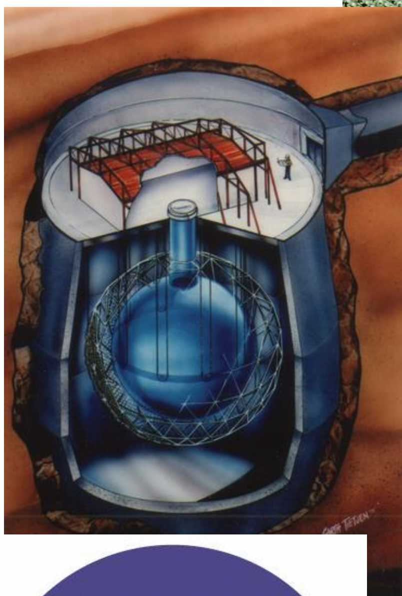
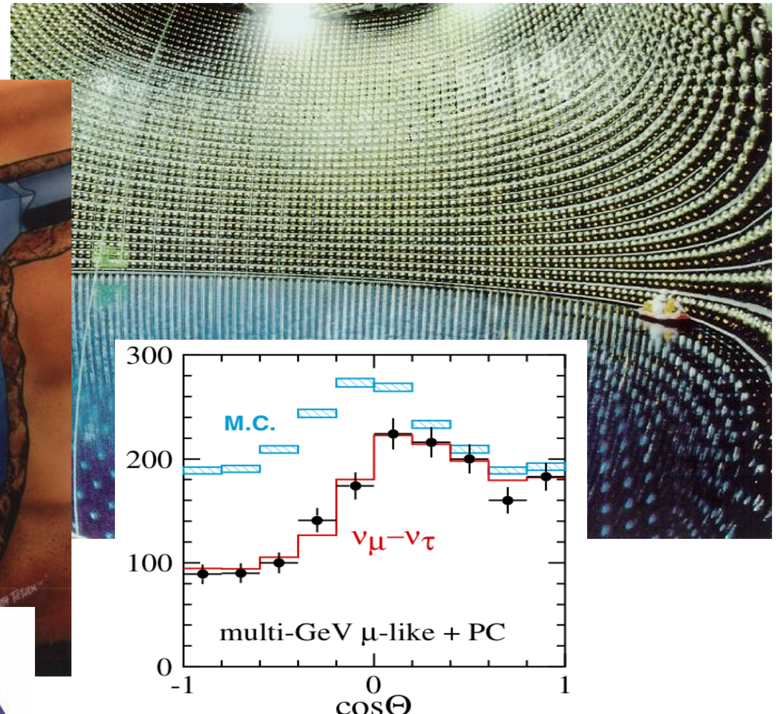
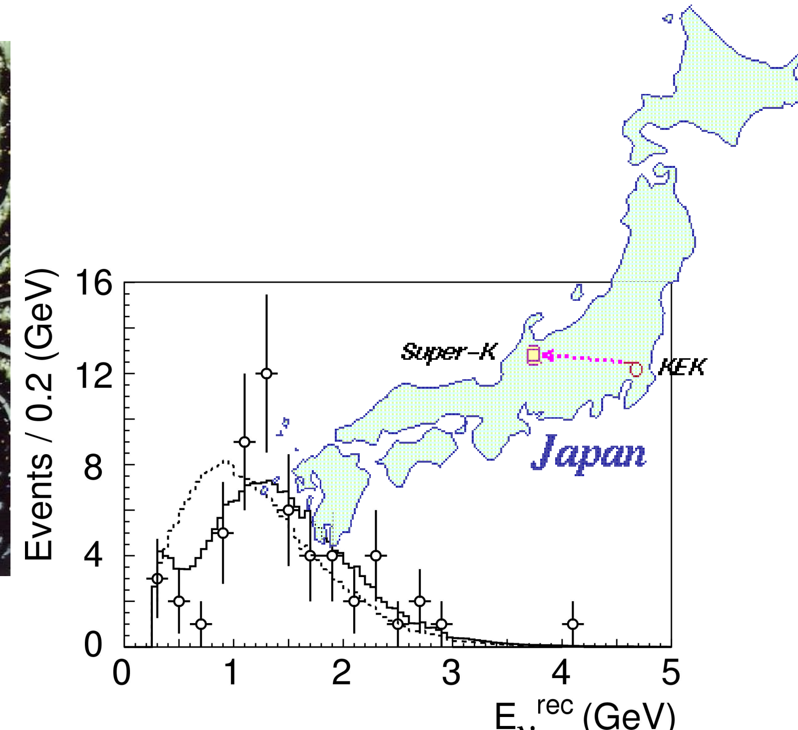
Boston University
Brookhaven National Lab, Feb 8, 2007

An Era of Discovery in Neutrino Physics







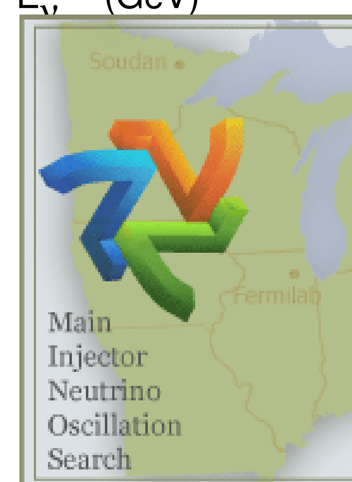
Kam LAND

Kamioka Liquid scintillator Anti-Neutrino Detector

The Blame

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_{m_a} \\ \nu_{m_b} \end{pmatrix}$$

$$\rightarrow P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

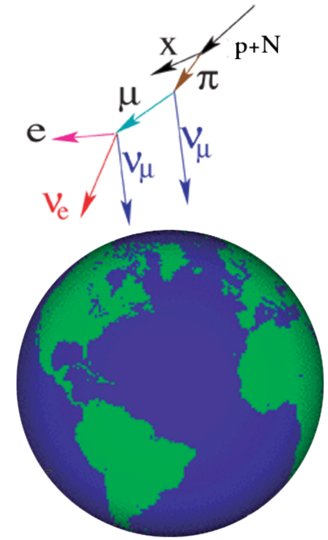


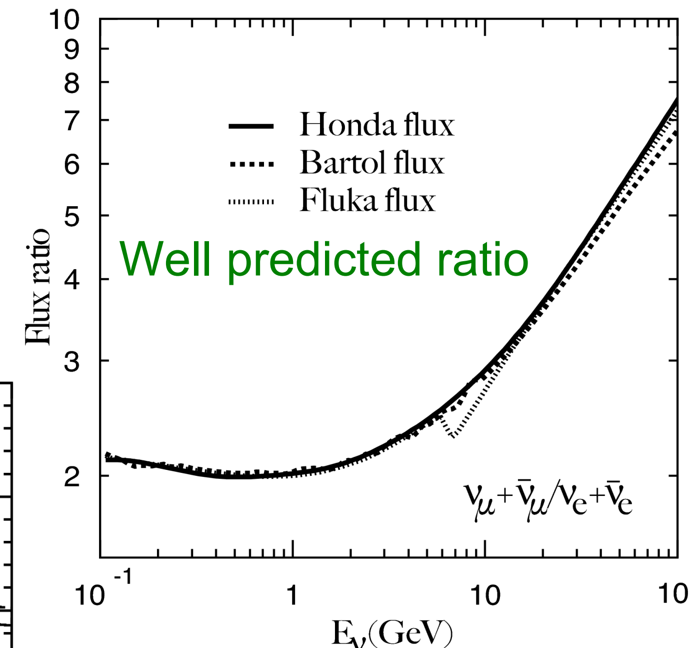
Outline

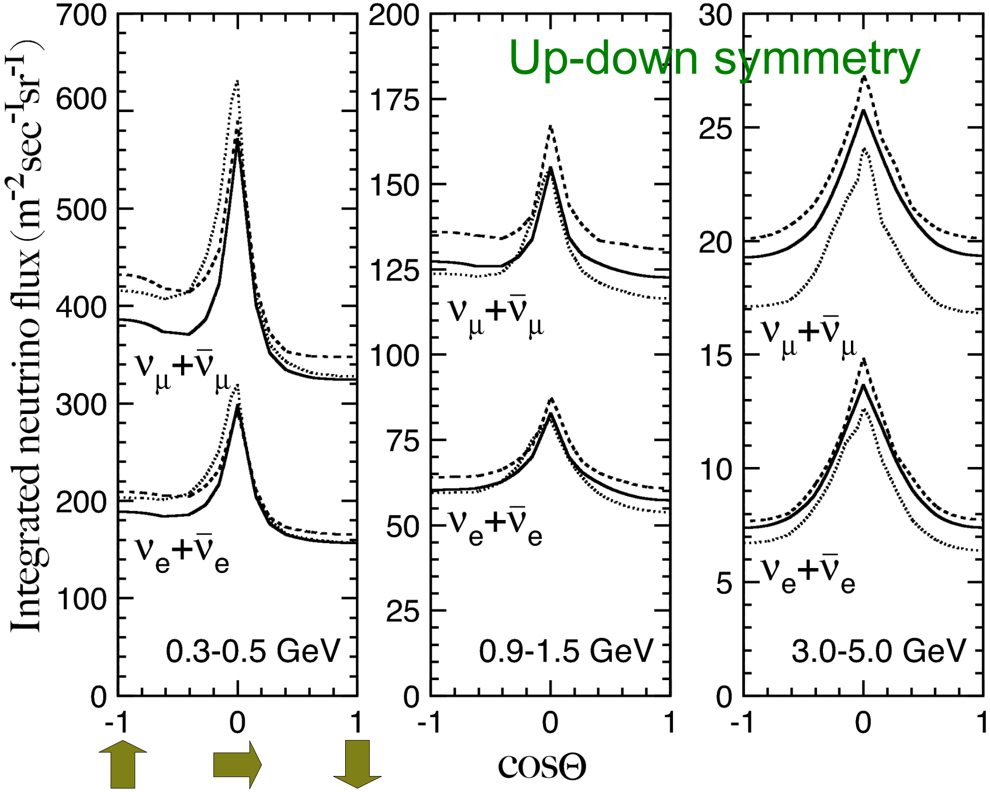
- Atmospheric neutrinos, Super-K experiment and events
- Standard ν_μ-ν_τ oscillation analysis
- Sterile neutrino as a alternative to tau neutrino
  - ν_μ-ν_τ mixing vs ν_μ-ν_s mixing
  - An admixture analysis
- Neutrino oscillations induced by the violations of Lorentz (LIV) and CPT (CPTV) invariance
  - Plausibility and allowed limits
- Vanishing neutrinos caused by neutrino decoherence and neutrino decay
  - Plausibility and allowed limits
- Summary and conclusions

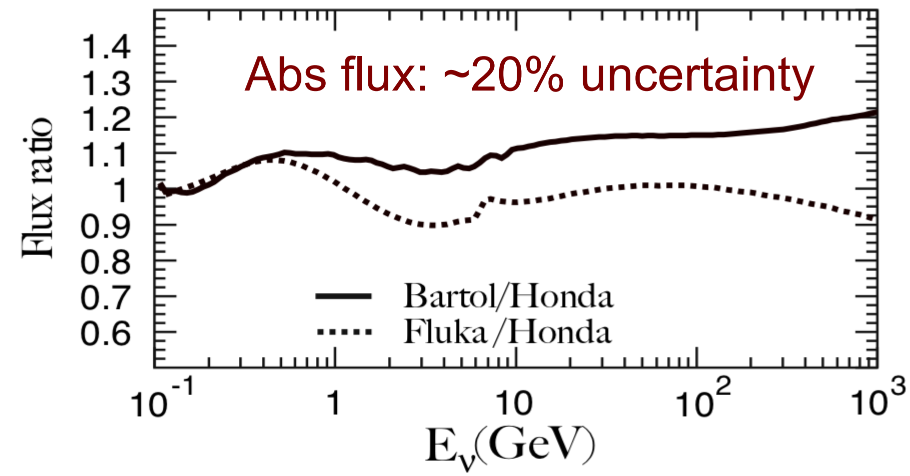
Atmospheric Neutrinos

- A large uncertainty on the absolute flux
- Good knowledge on flavor ratio
- Up-down symmetric



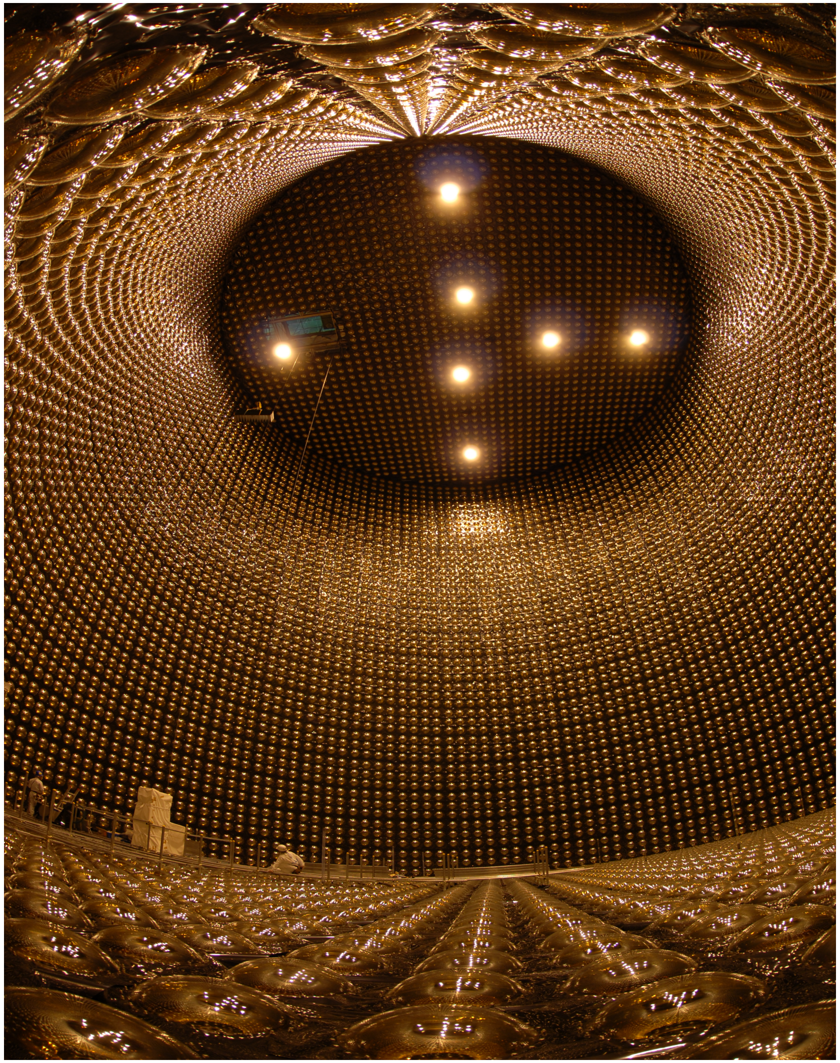






Super-Kamiokande Collaboration

- 140 collaborators from 35 institutes of 5 countries



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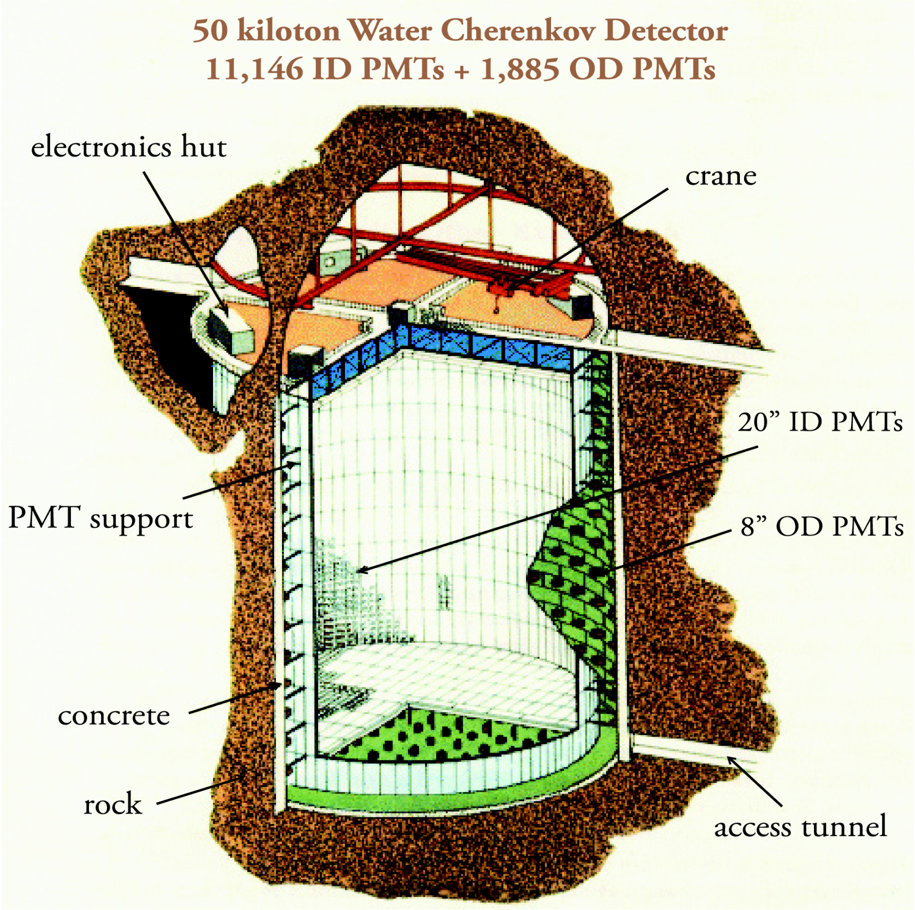
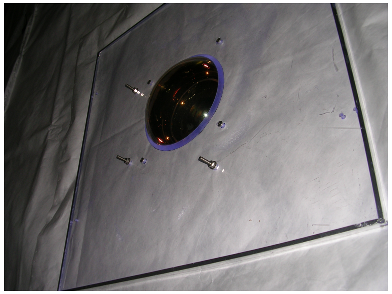
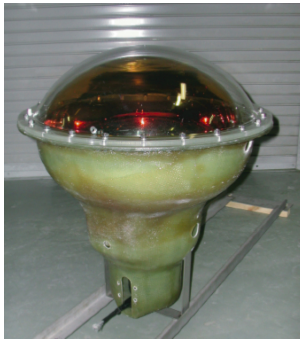
Super-Kamiokande Experiment

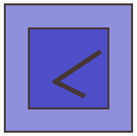
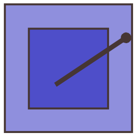
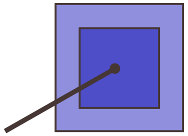
- A 50 kt water Cherenkov detector
  - Inner detector and outer detector optically separated
  - ID: 25in PMTs; gaps filled by black sheet
  - OD: 8 inch PMTs with wavelength shifters, wall covered by reflective Tyvek
- Operating periods
  - **SK-I: 1996 – 2001**
    - 1489 days livetime
    - ~40% ID coverage
  - **SK-II: 2003 – 2005**
    - 804 days livetime
    - Half ID tubes (acrylic cover & FRP), ~20% coverage
  - **SK-III: since Summer 2006**
    - ID tubes (acrylic cover & FRP) fully recovered

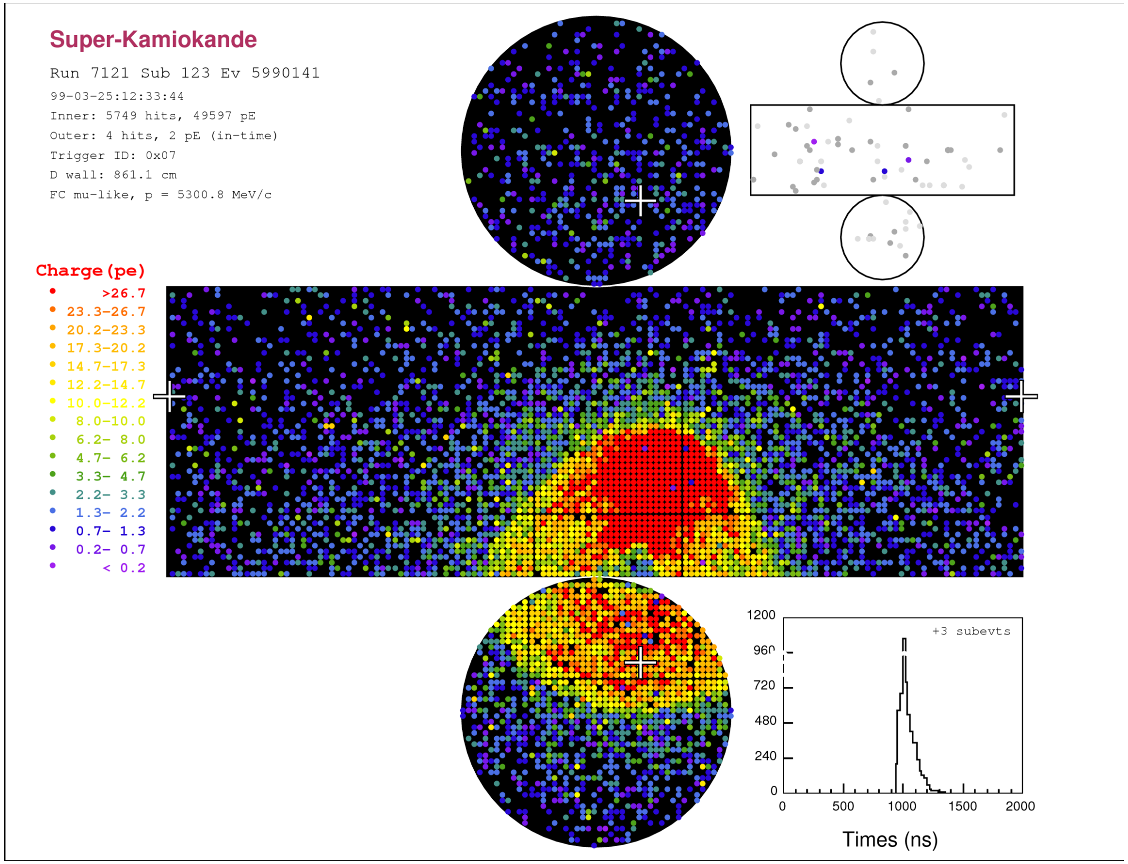






Neutrino Events

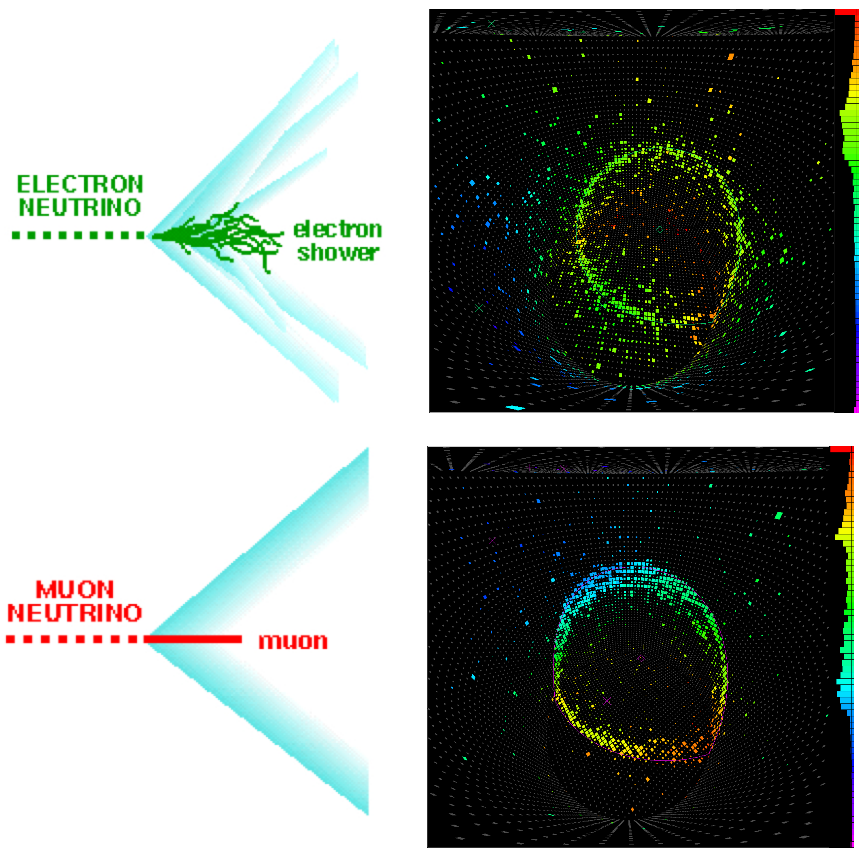
- Neutrino interaction
  → charged particles
  → Cherenkov radiation
  → recorded by PMTs
- Super-K event categories
  - Fully contained 
  - Partially contained 
  - Upward going μ 

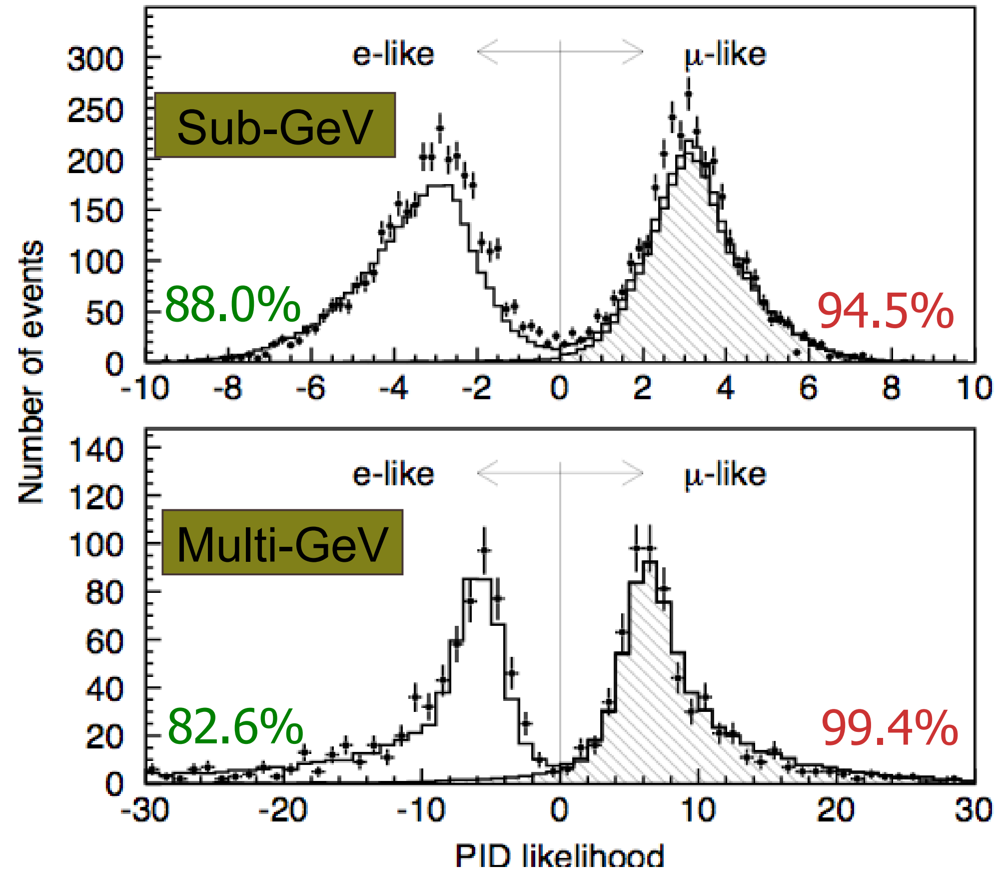


Event Reconstruction

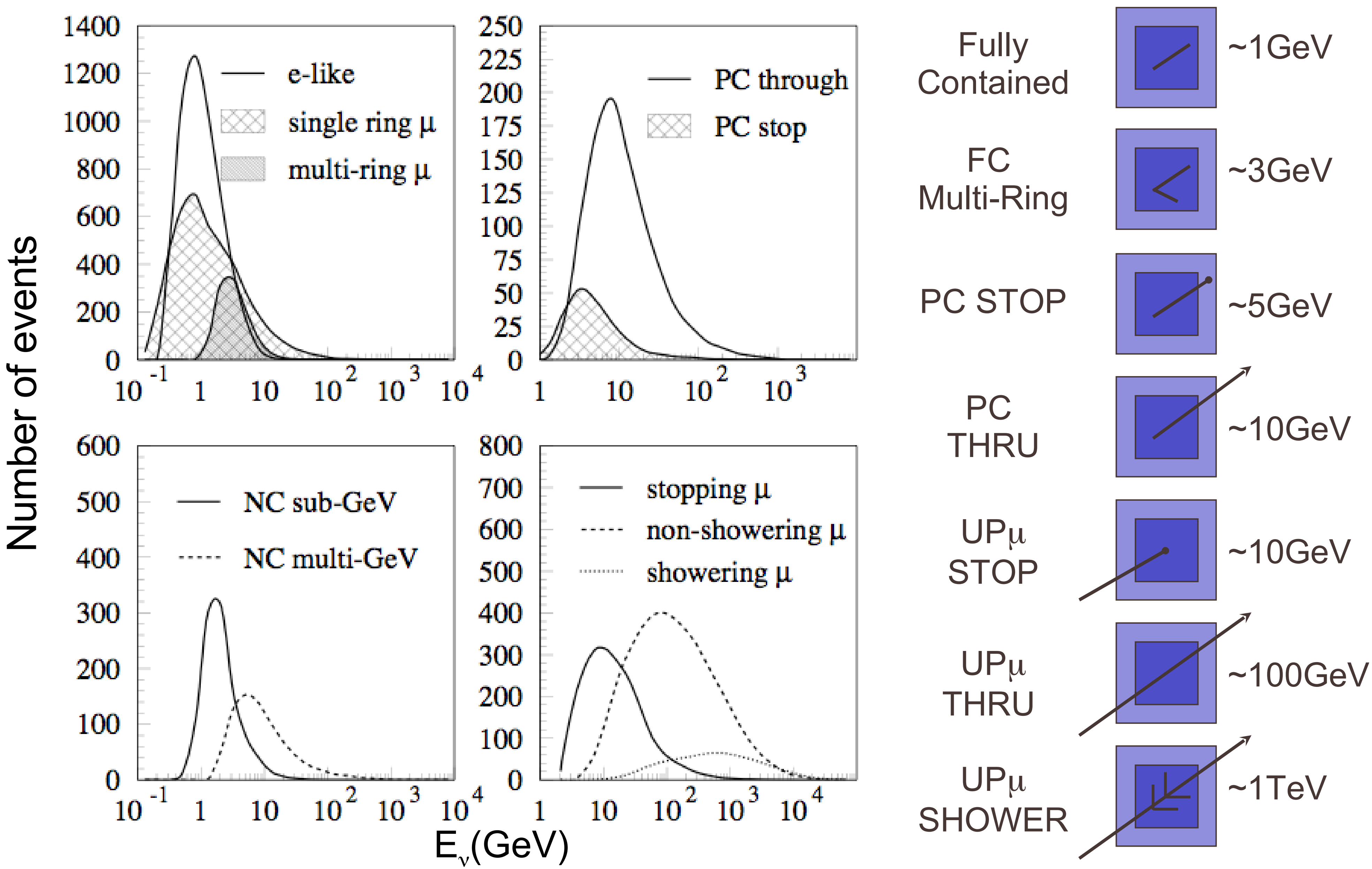
- Vertex finding
- Ring recognition
- PID (e-/μ-like)
- Momentum reconstruction

FC Single Ring Events

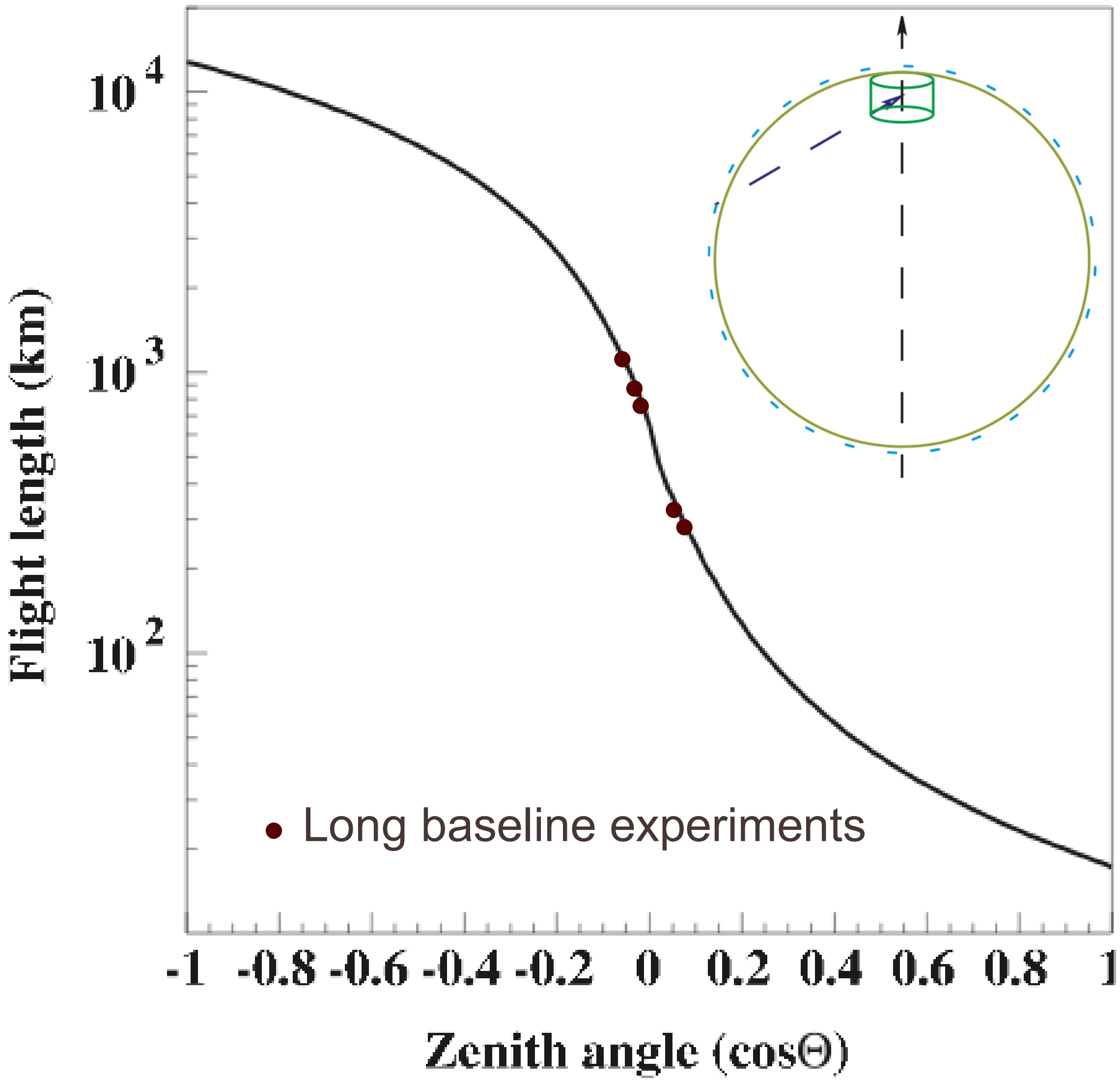


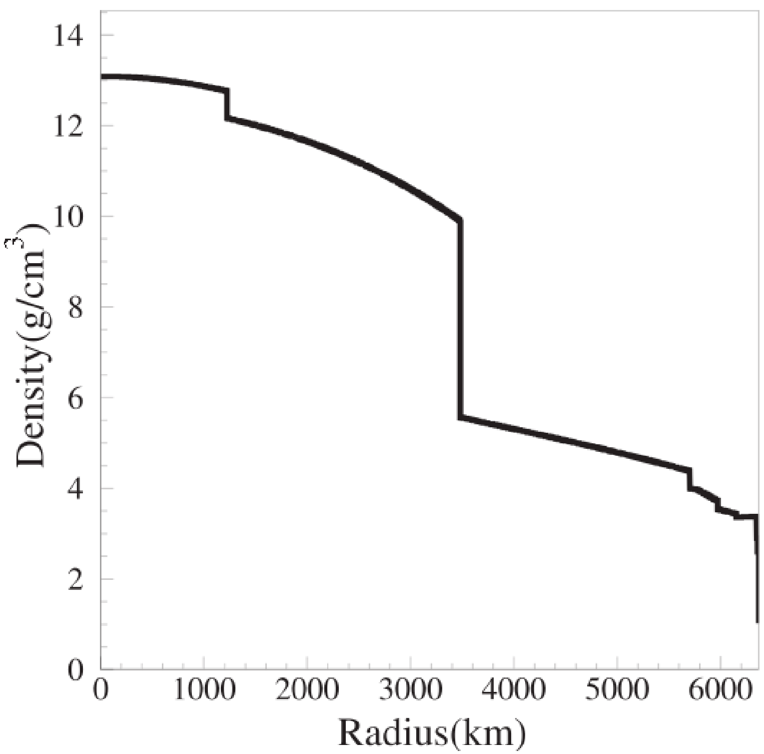


Five Decades of Energy



Four Decades of Pathlengths

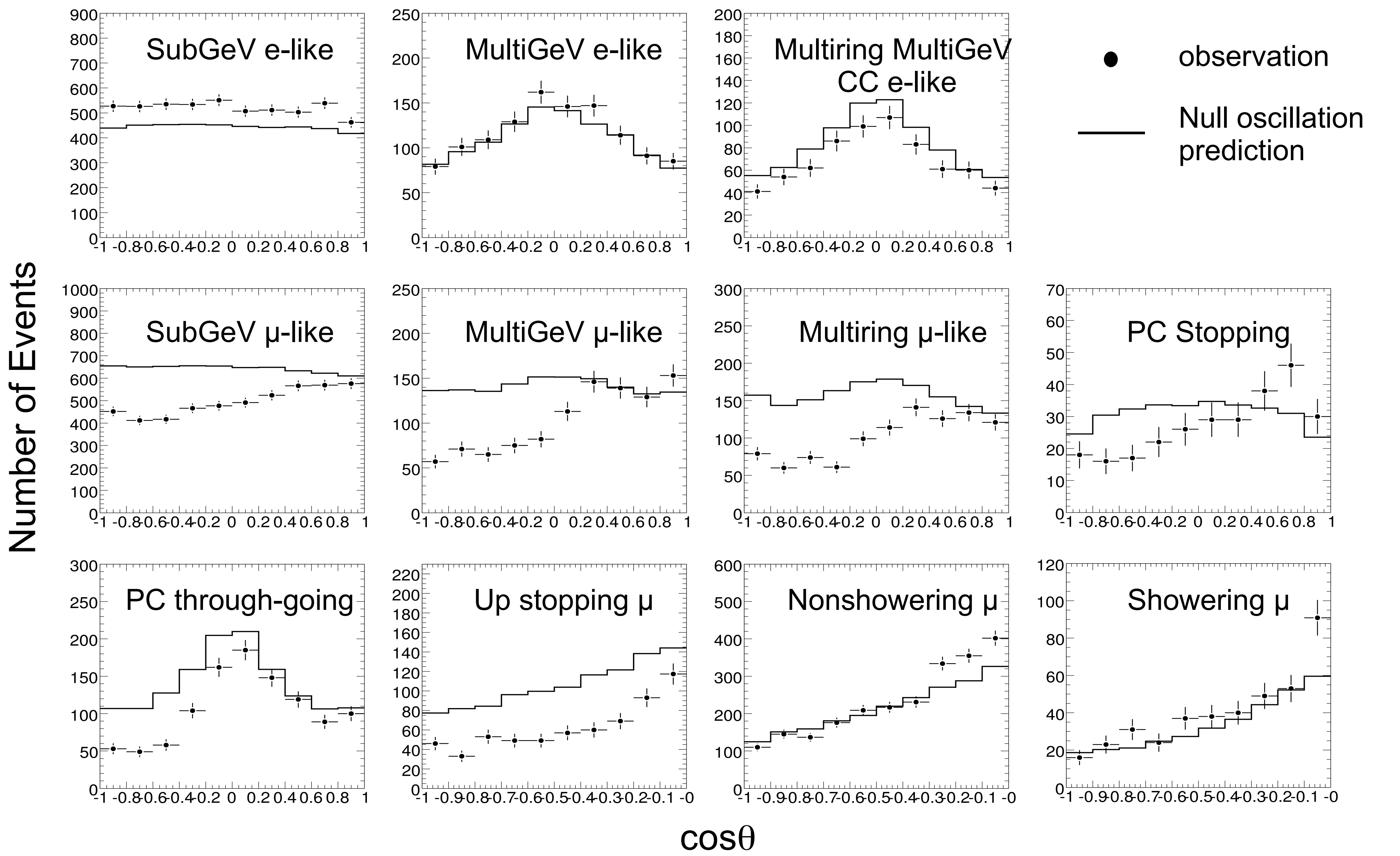




- →Large ranges of *L* and *E*
- →Various matter densities

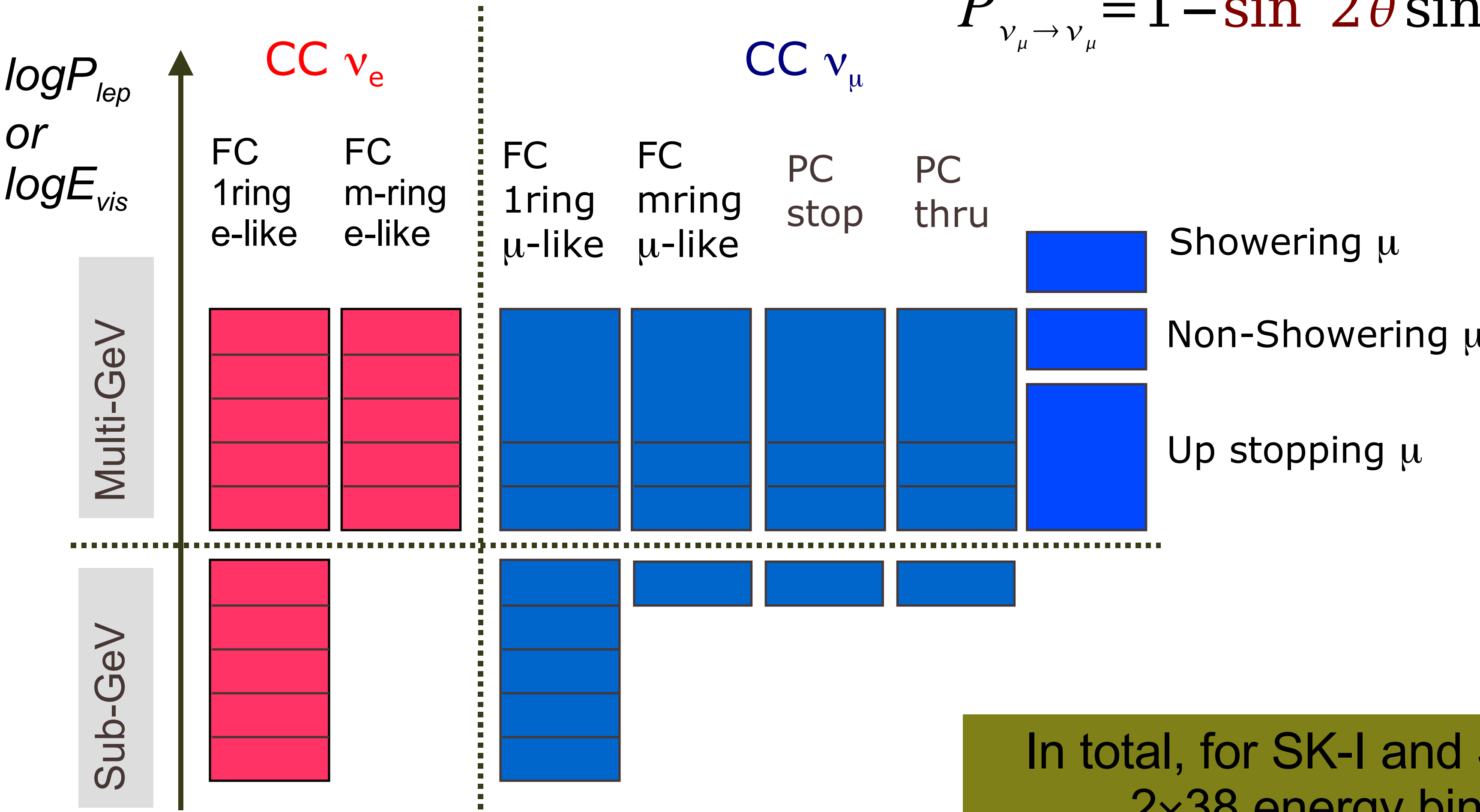
⇒ great advantages for studying exotic phenomena

Atmospheric Neutrino Observations



Data Analysis: Binning

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$



e-like events for flux normalization

μ-like events for oscillation signal

In total, for SK-I and SK-II, 2×38 energy bins ×10 zenith bins = 760 bins

Data Analysis: Pull Method

$$\chi^2 = \sum_{i=1}^{N} 2\left(N_i^{\exp} - N_i^{\mathrm{obs}} - N_i^{\mathrm{obs}} \ln \frac{N_i^{\mathrm{obs}}}{N_i^{\exp}}\right) + \sum_{j=1}^{M} \left(\frac{\epsilon_j}{\sigma_j}\right)^2$$

Data bins: likelihood ratio

Systematic uncertainties: Gaussian

Expected number of events

$$\begin{cases} N_i^{\exp} = \left(1 + \sum_{j=1}^{M} f_i^j \epsilon_j\right) N_i^{\exp 0} \\ N_i^{\exp 0} = P_{\mathrm{survival}}(\text{model x with parameters } \vec{x}) N_i^{\mathrm{nosc}} \end{cases}$$

Expected number of events without considering systematics

Survival probability predicted by model x

Null oscillation prediction

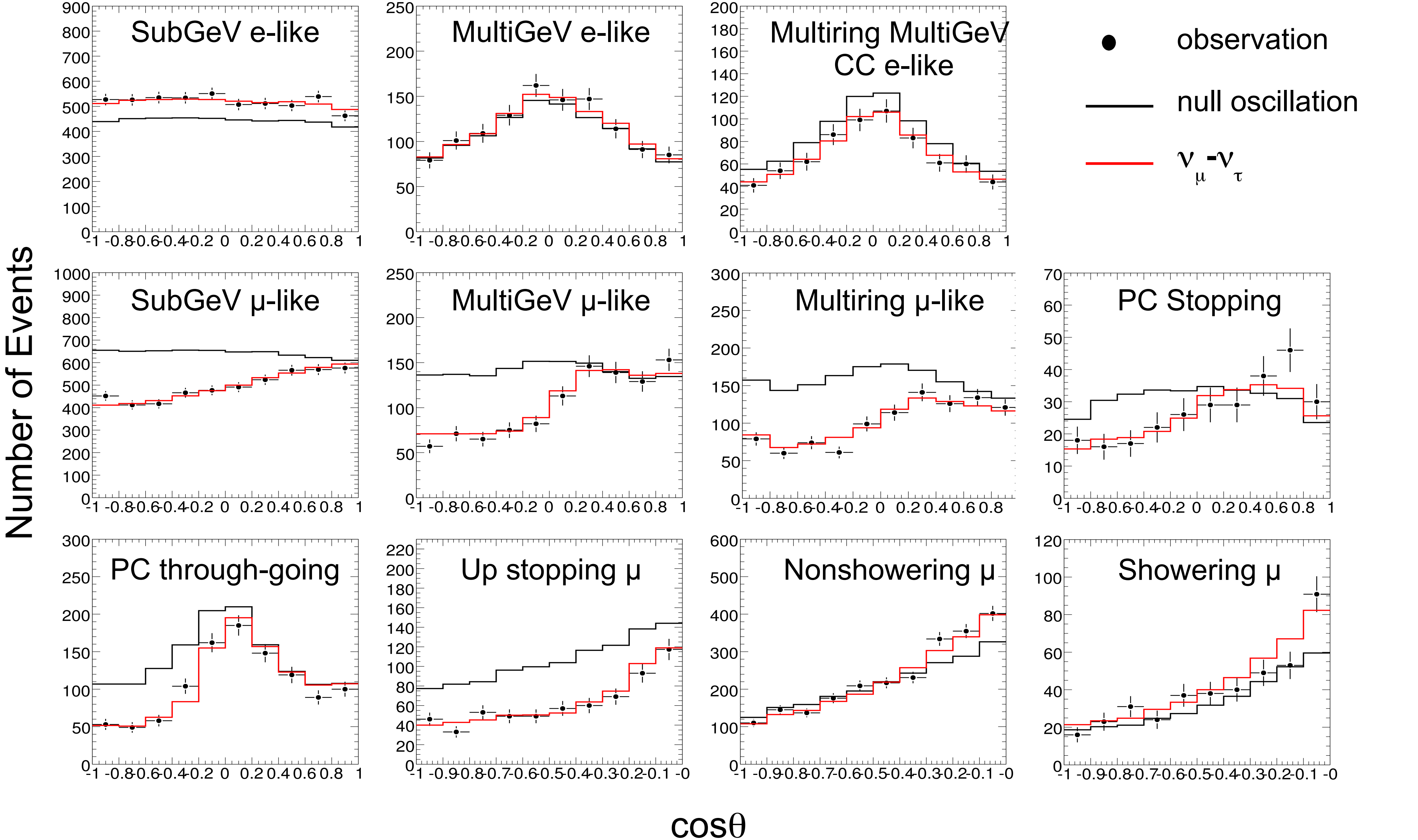
Plug in different models and find the minimum chi-squares

Combining SK-I and SK-II

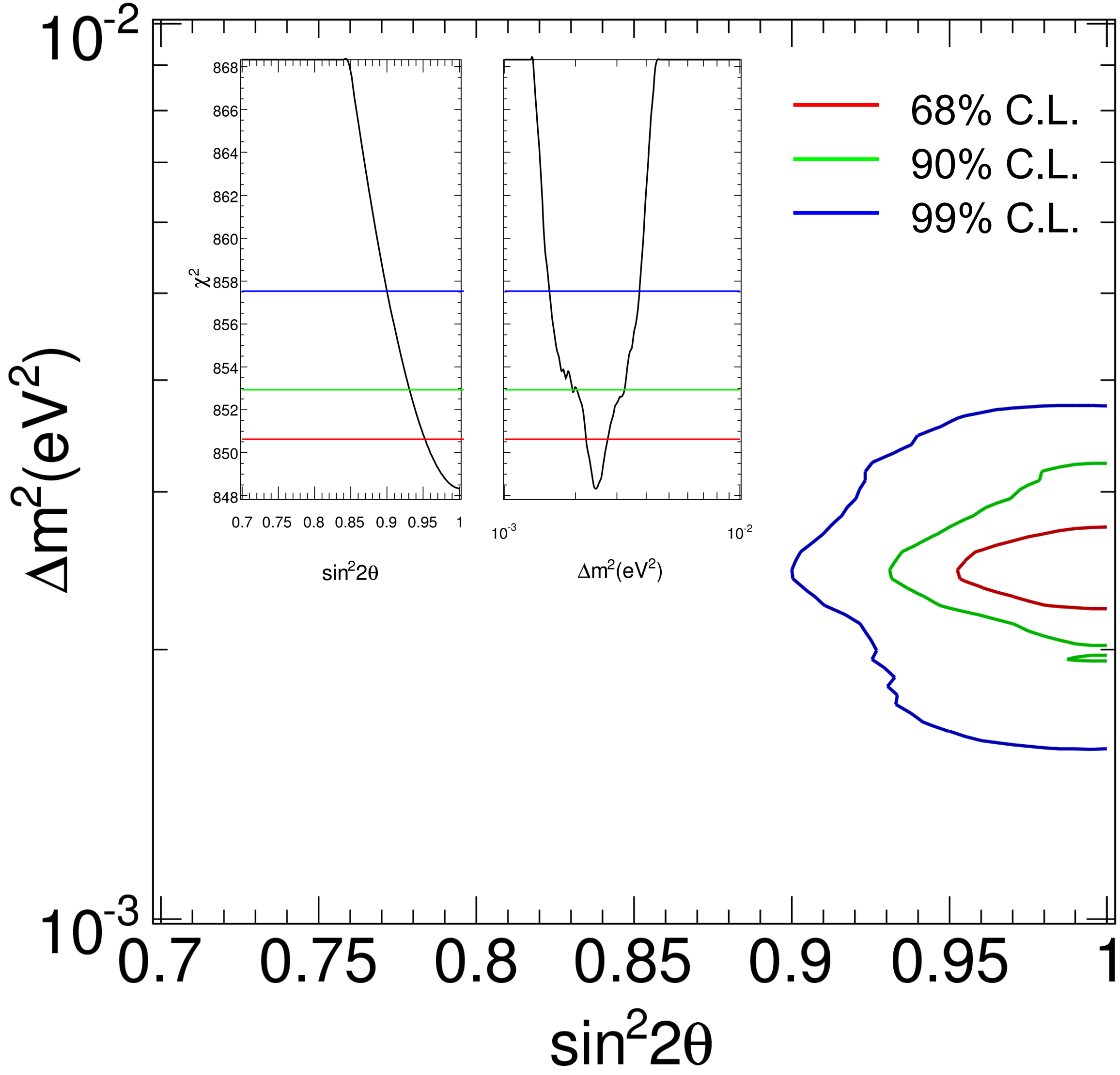
- Data bins are considered as independent observations
- Systematic uncertainties
  - Identical for SK-I and SK-II
    - Atm neutrino flux (14)
    - Neutrino interaction (12)
  - Independent for SK-I and SK-II
    - Solar activity (1)
    - Data selection and event reconstruction (21)

→In total, 70 systematic uncertainties for SK-I and SK-II combined analysis

Zenith Distribution Explained by ν_μ-ν_τ Oscillation

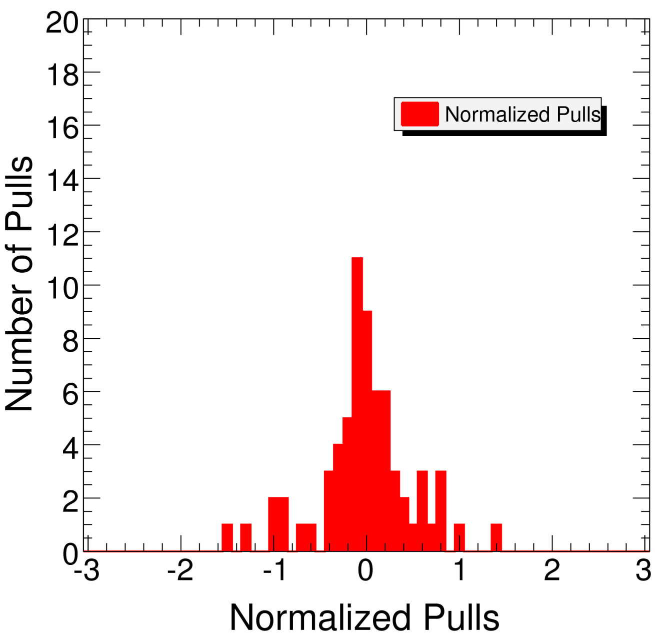


Standard Mixing Parameters



$$\nu_\mu \rightarrow \nu_\tau$$

$$\sin^2 2\theta = 1$$
$$\Delta m^2 = 2.5\times 10^{-3}\, eV^2$$
$$\chi^2 / dof = 839.7/755$$
$$p-value = 18\,\%$$



Must It Be Tau Neutrino?

- If three flavors of neutrinos, there is no choice
  - A ν_μ-ν_e oscillation does not explain the Super-K observation
  - Chooz and Palo Verde: no oscillation at the scale $\Delta m^2 \sim 10^{-3} eV^2$
- LEP experiments: Z decay width consistent with 3 neutrino flavors, $N_\nu = 2.992 \pm 0.020$

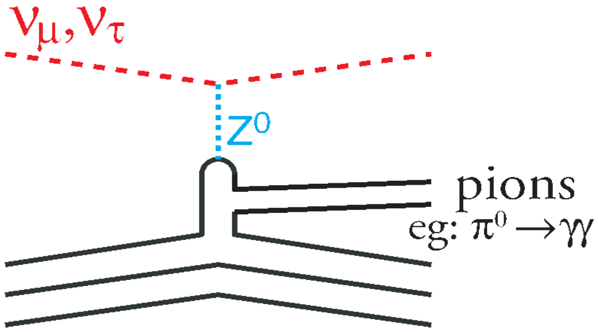
→ But sterile neutrinos (ν_s: no electric, strong or weak charge) can still fit in the picture

  - Some theoretical models do predict the existence of sterile neutrinos
  - Some data are in favor of the existence of sterile neutrinos
    - ✓ Sterile neutrino may solve the LSND anomaly
    - ✓ Sterile neutrino can help solve the nuclear synthesis problem during the supernova R-process

Signatures of the Sterile Neutrinos

Based on the definition of sterile neutrino, ν_μ-ν_τ oscillation can be distinguished from ν_μ-ν_s oscillation in two ways

1. A trivial difference: neutral current events

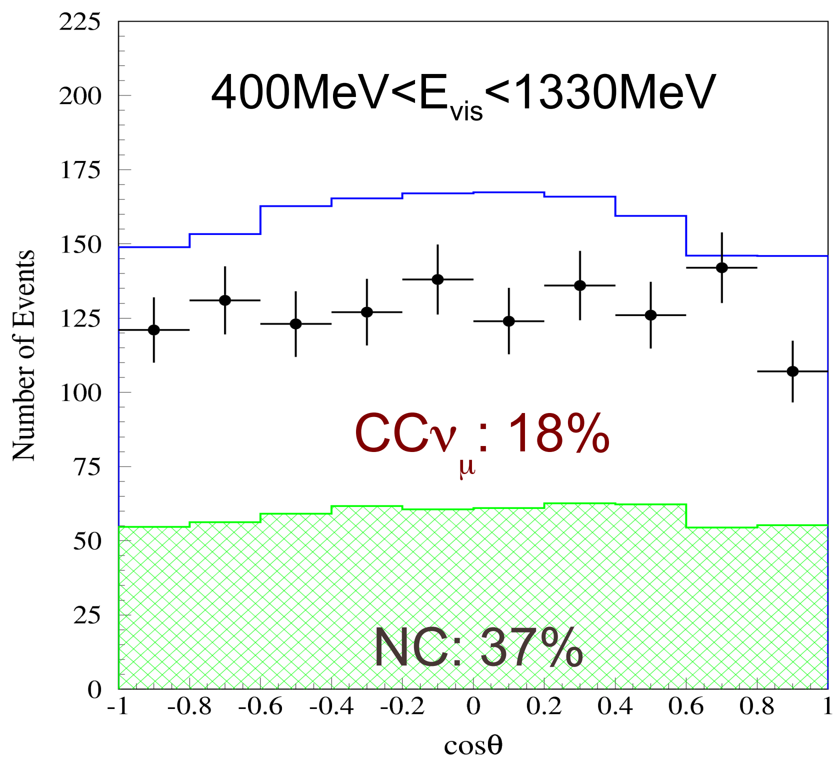


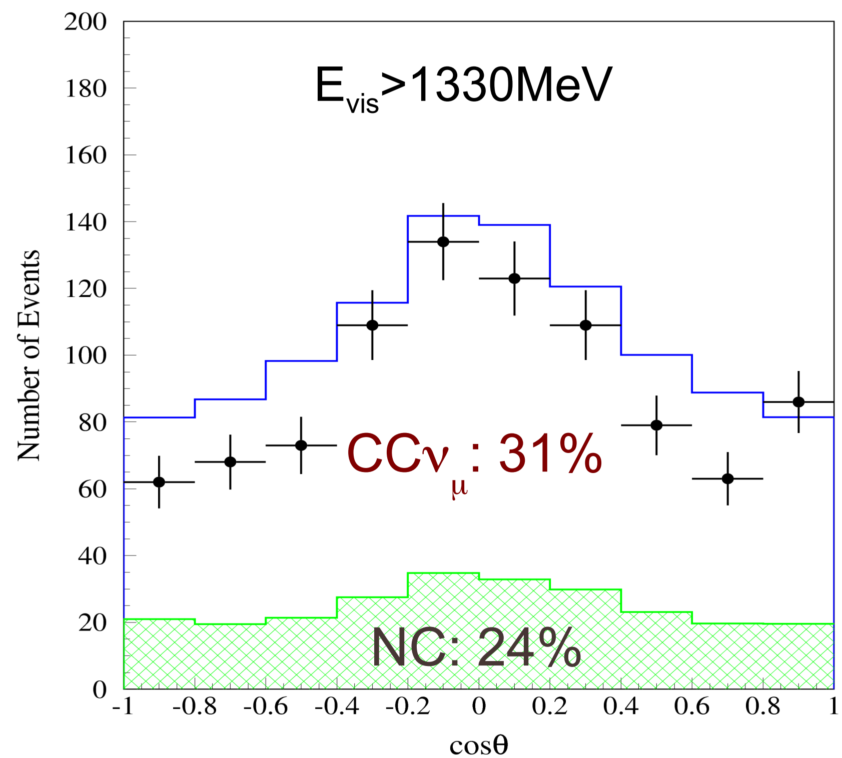
ν_s: no interaction

2. A more subtle effect: Matter Effect

1. NC Events at Super-K

- Multi-ring events: neutral pions are the NC signature at SK
- Brightest ring e-like
- E_{vis}>400MeV: Low energy events do not point well





2. Matter Effect

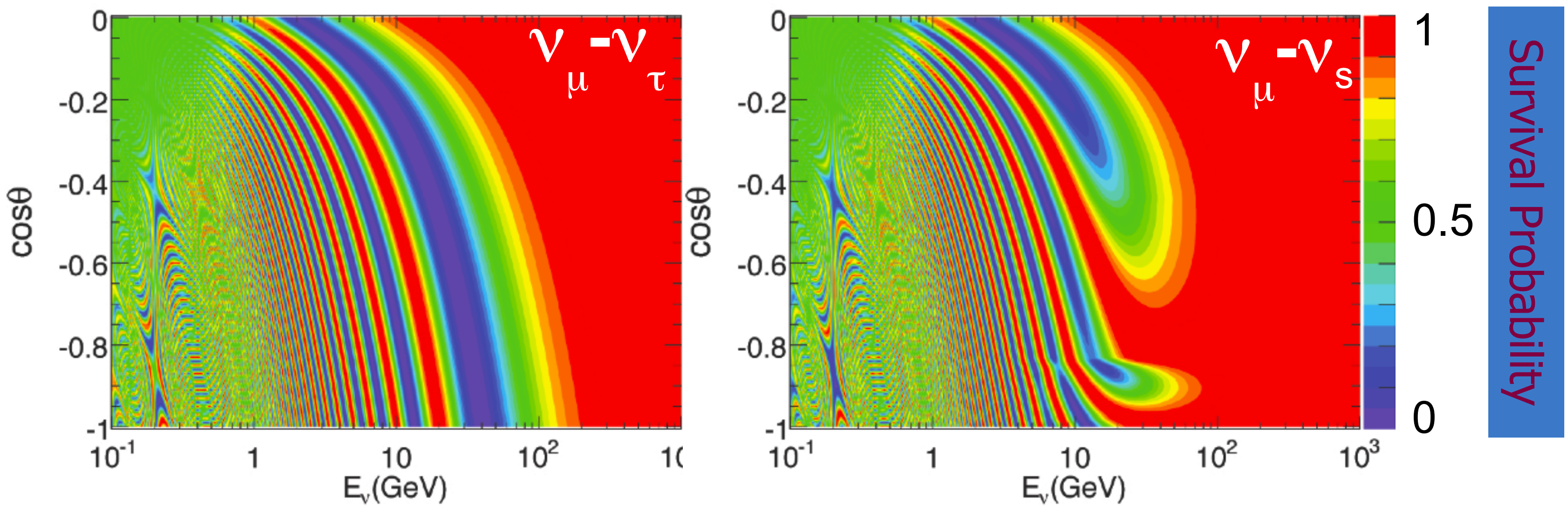
- If two neutrino flavors interact differently in matter

$$P_{osc} = \sin^2 2\theta_M \sin^2 \frac{\Delta m_M^2 L}{4E} \qquad \begin{cases} \sin^2 2\theta_M = \dfrac{\sin^2 2\theta}{(2E\Delta V/\Delta m^2 - \cos 2\theta)^2 + \sin^2 2\theta} \\ \Delta m_M^2 = \Delta m^2 \sqrt{(2E\Delta V/\Delta m^2 - \cos 2\theta)^2 + \sin^2 2\theta} \end{cases}$$

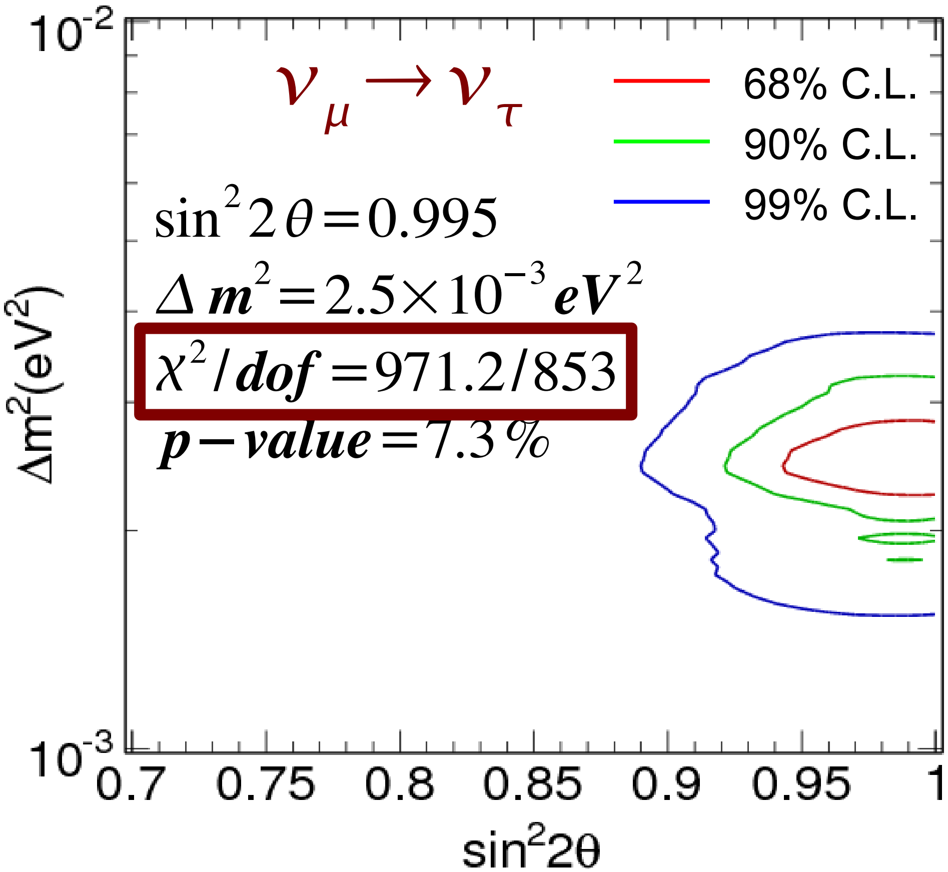
- ν_μ-ν_s: ν_μ and ν_s interact with matter differently $\quad \Delta V = \mp\sqrt{2}\, G_F \dfrac{\rho_n}{2}$

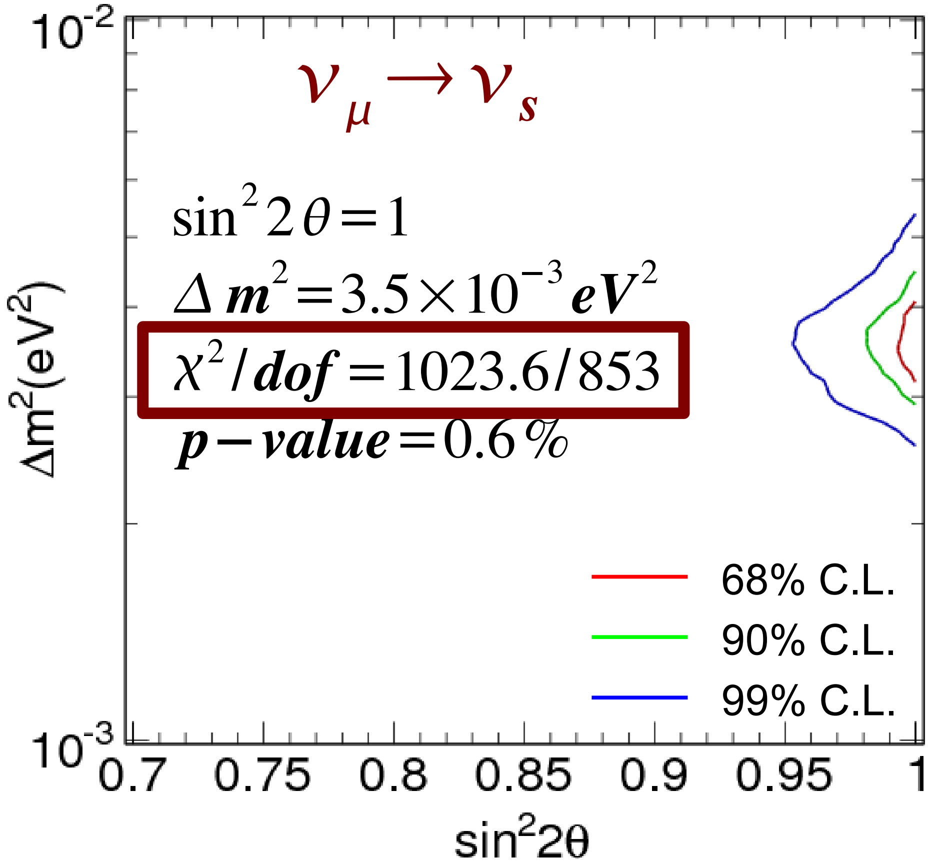
  $\Rightarrow$ matter effect $\Rightarrow$ oscillation is suppressed

Survival probability of ν_μ crossing Earth: $\Delta m^2 = 2.5\times10^{-3}\mathrm{eV}^2$, $\sin^2 2\theta = 1$



Tau Neutrino vs Sterile Neutrino

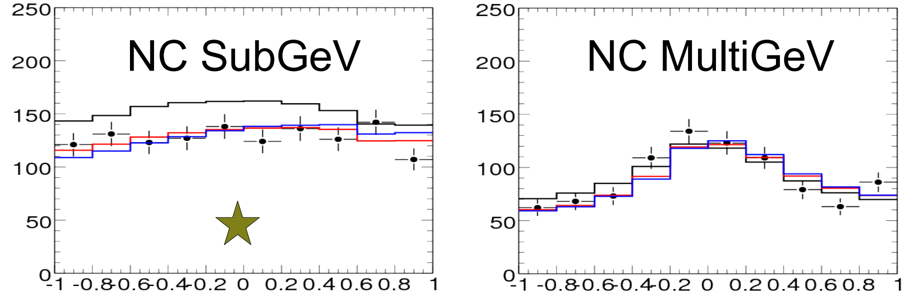




P-values calculated using toy MC method.

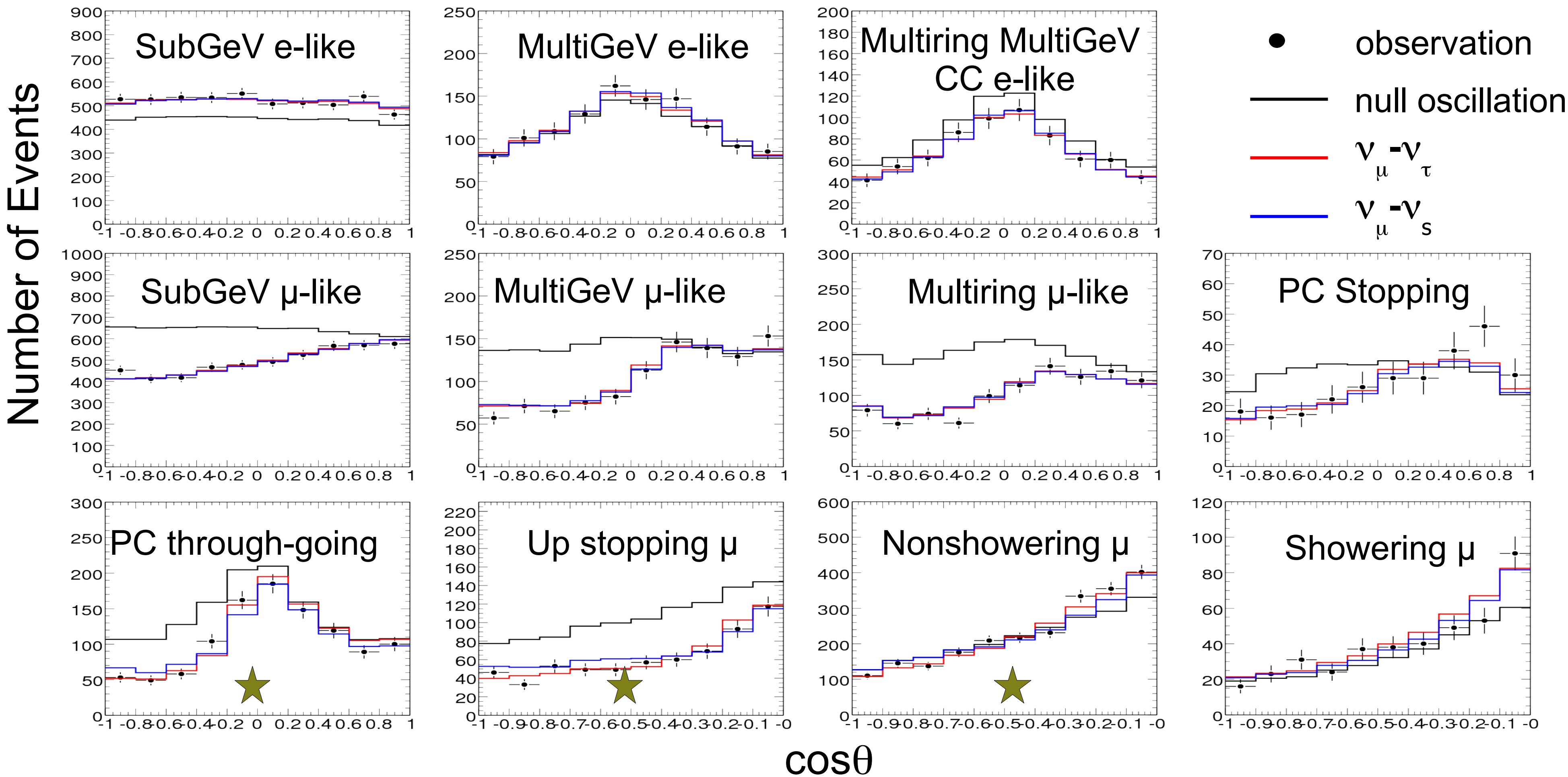
- Exclusion Level: 7.2σ

Comparison of Zenith Distributions



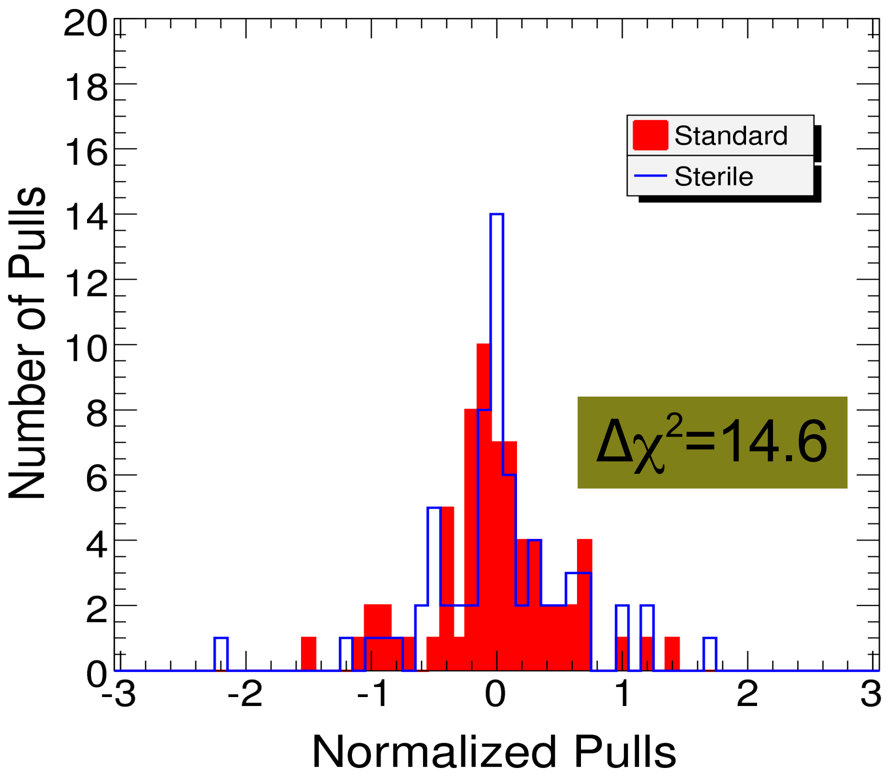
χ^2 Breakdown

	Data bins	Systematics
χ^2 (Standard)	952.9	18.3
χ^2 (Sterile)	990.7	32.9
Difference	37.8	14.6



$\Delta\chi^2$ Contribution Breakdown

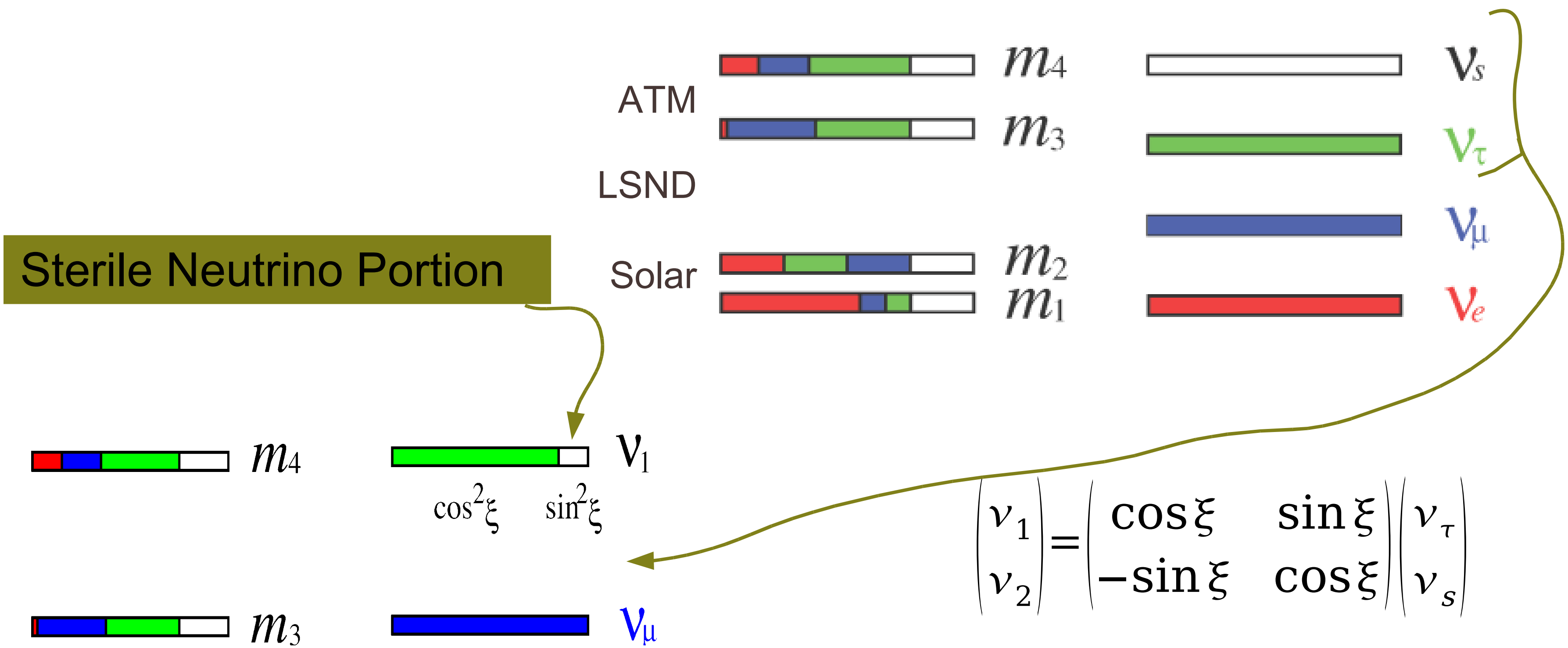
Single Ring SubGeV e-like	0.8
Single Ring MultiGeV e-like	-2.1
Multi-Ring MultiGeV CC e-like	0.8
Single Ring SubGeV μ-like	-1.3
Single Ring MultiGeV μ-like	-2
Multi-Ring μ-like	3.8
NC-Enhanced SubGeV	5
NC-Enhanced MultiGeV	1.2
PC Stopping μ	2.9
PC Through-Going μ	12.3
Upward Stopping μ	7.2
Upward NonShowering μ	11.2
Upward Showering μ	-1.5
TOTAL	37.8



- The right energies and baselines of those events give the strongest matter effects

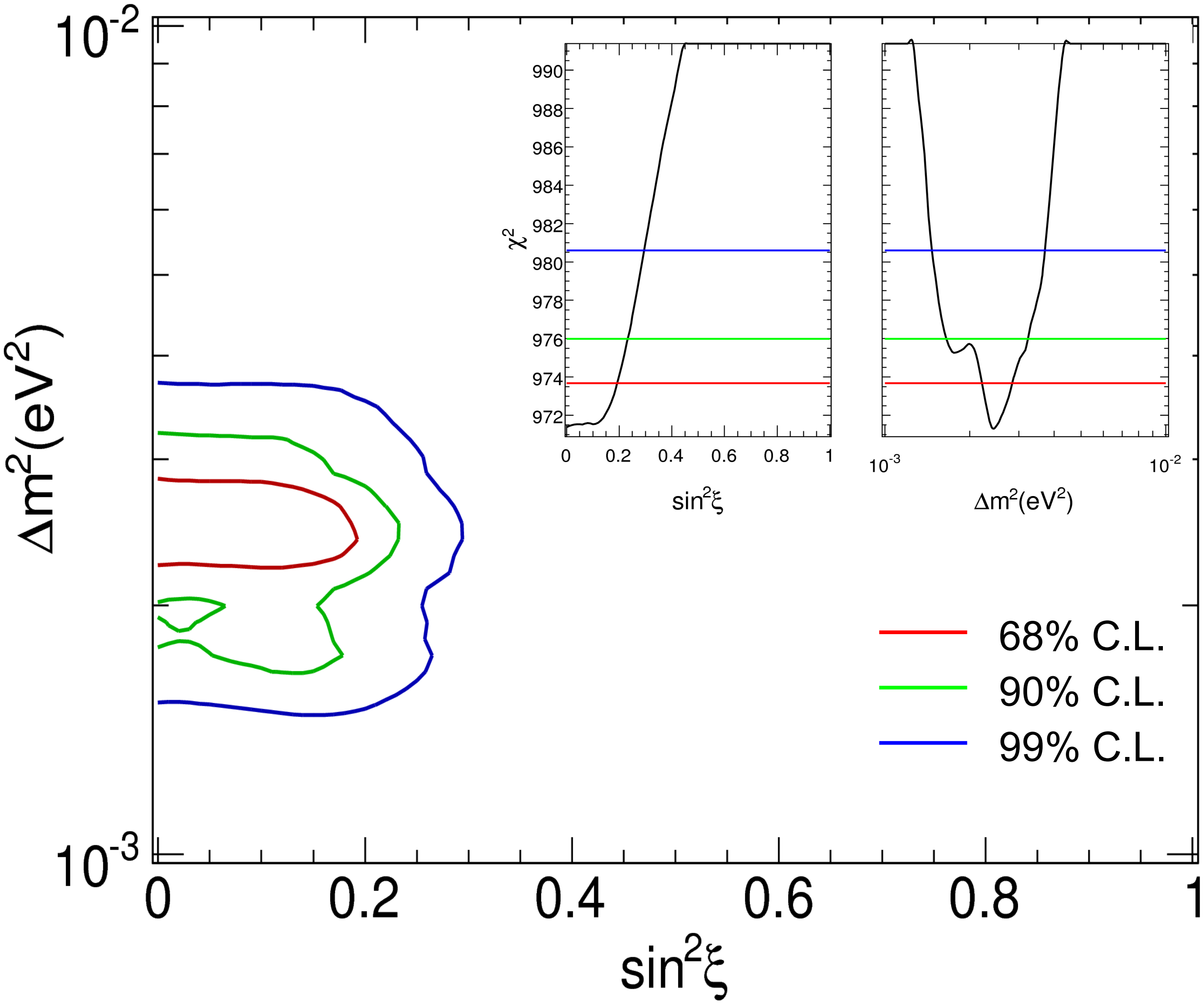
An Admixture Case

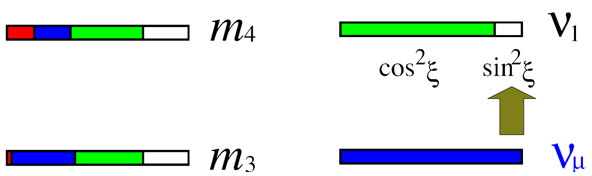
- Admixtures are model dependent
- This analysis is base on Fogli *et al* PRD 63(053008), 2001
  - A 2+2 mass hierarchy model
  - Constructing two superposition states of ν_s and ν_τ → two flavor mixing



$$\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}=\begin{pmatrix}\cos\xi & \sin\xi\\ -\sin\xi & \cos\xi\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \nu_s\end{pmatrix}$$

Admixture Allowance





- Allowed sterile neutrino admixture limit at 90% C.L.: $\sin^2\xi < 23\%$

Violations of Lorentz and CPT Invariance

→Neutrino oscillations without masses

- Oscillation is caused by modified dispersion relation

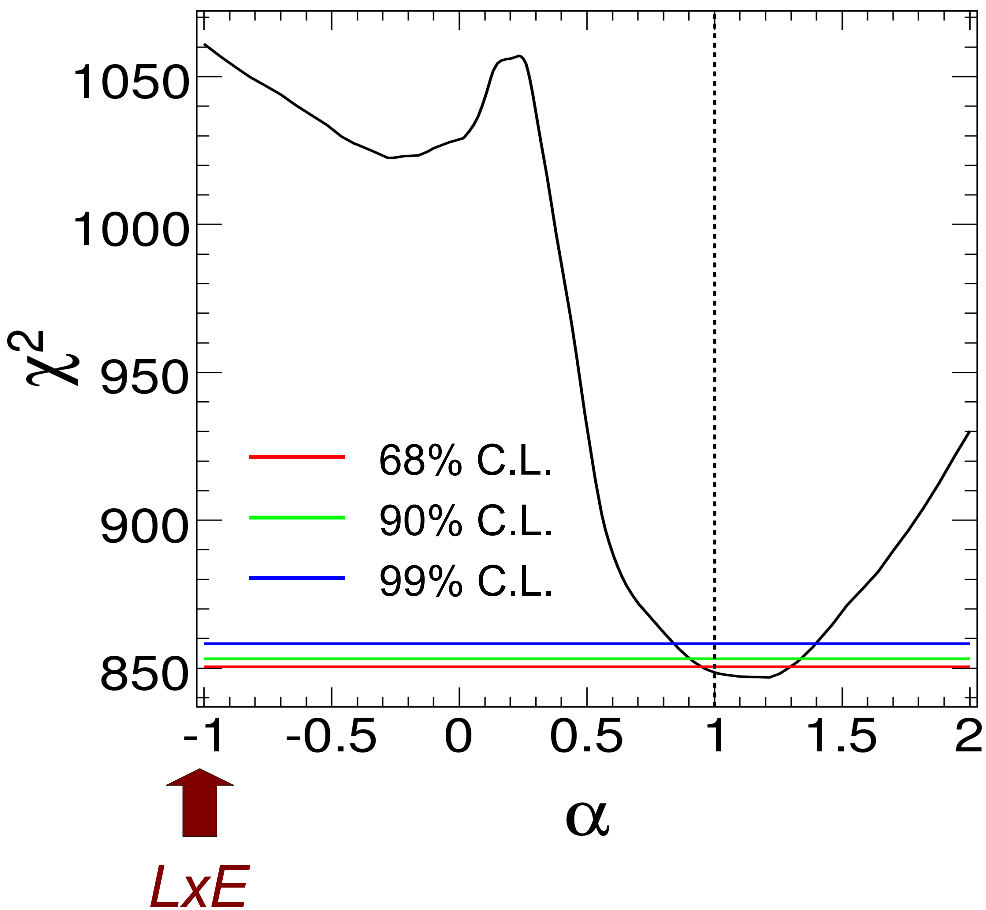
→Important fundamental symmetries

- Broken at some high energy level? (e.g. Quantum Gravity)
- SK neutrino energies and pathlengths provide advantages checking them

- Minimal Standard Model Extension constructed by Kostelecky *et al,* hep-ph/0403088
  - $\mathcal{L} = a_{\mu AB}\bar{L}_A\gamma^\mu L_B + \frac{1}{2} i c_{\mu\nu AB}\bar{L}_A\gamma^\mu \overleftrightarrow{D}^\nu L_B$
  - The first term violates both CPT (CPTV) and Lorentz invariance (LIV); the second term only violates Lorentz invariance
  - Two rotationally invariant cases (only time components non-zero)
    - Coleman and Glashow, PRD 59(116008), 1999
    - Barger *et al*, PRL 85(5055), 2000

Lorentz Invariance Violation

- $-c_{AB}^{TT}(L_A \gamma^0 \partial^0 L_B + \partial^0 L_A \gamma^0 L_B) \Rightarrow \sin^2(\Delta c L E)$ oscillation
  - Mixing between different "maximum attainable velocity" eigenstates
- A more general form: $P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta \sin^2 \kappa L/E^\alpha$



- *LxE* oscillation is strongly disfavored
  - Excluded at ~14σ
- *L/E* is within the 1st σ
  - 1.16+0.14/-0.21
- A natural question: what is the scale LIV might appear?

LIV as a Sub-Dominant Effect

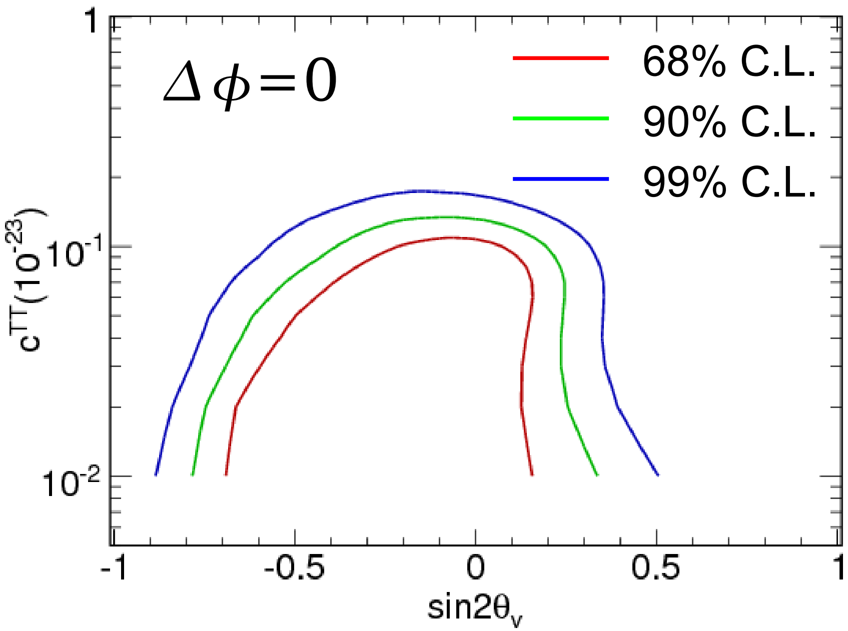
- Considering LIV as a sub-dominant effect
- Assuming best-fit parameter values for the standard oscillation

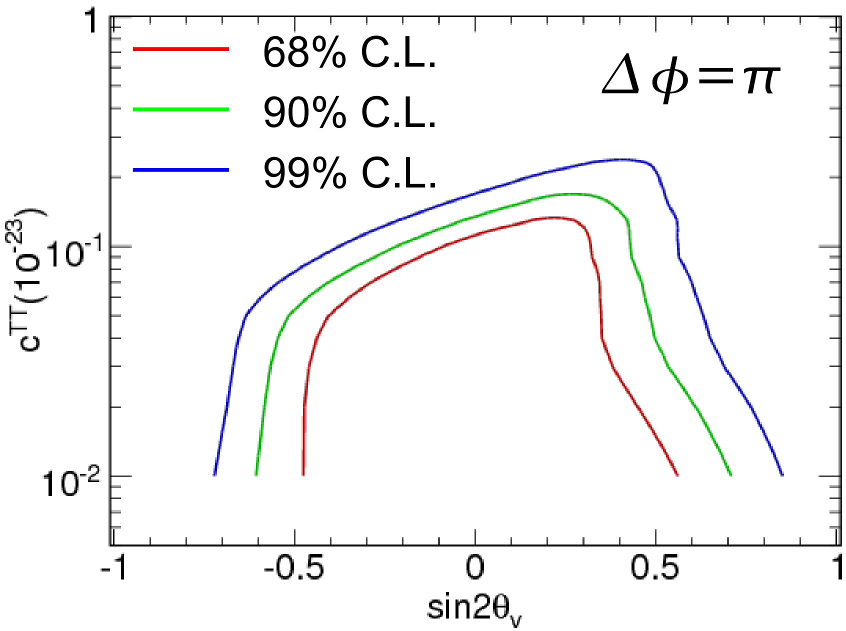
$$\boxed{P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\Theta \sin^2 \Omega}$$

$$\begin{cases} \tan 2\Theta = \dfrac{1+(E/E_c)^2 \sin 2\theta_v}{(E/E_c)^2 \cos 2\theta_v} \\ \Omega = 1.27\sqrt{(\Delta m^2 L/E)^2 \pm 4 c^{TT} \sin 2\theta_v L E + 4(c^{TT} L E)^2} \\ E_c = \sqrt{\dfrac{\Delta m^2}{2 c^{TT}}} \end{cases}$$

- c^{TT}: the difference of maximum attainable velocities
- θ_v: mixing angle between two different maximal attainable velocity eigenstates
- "+/-": the 0/π phase difference between the mass mixing matrix and the maximum attainable velocity mixing matrix

Limits on LIV Scale





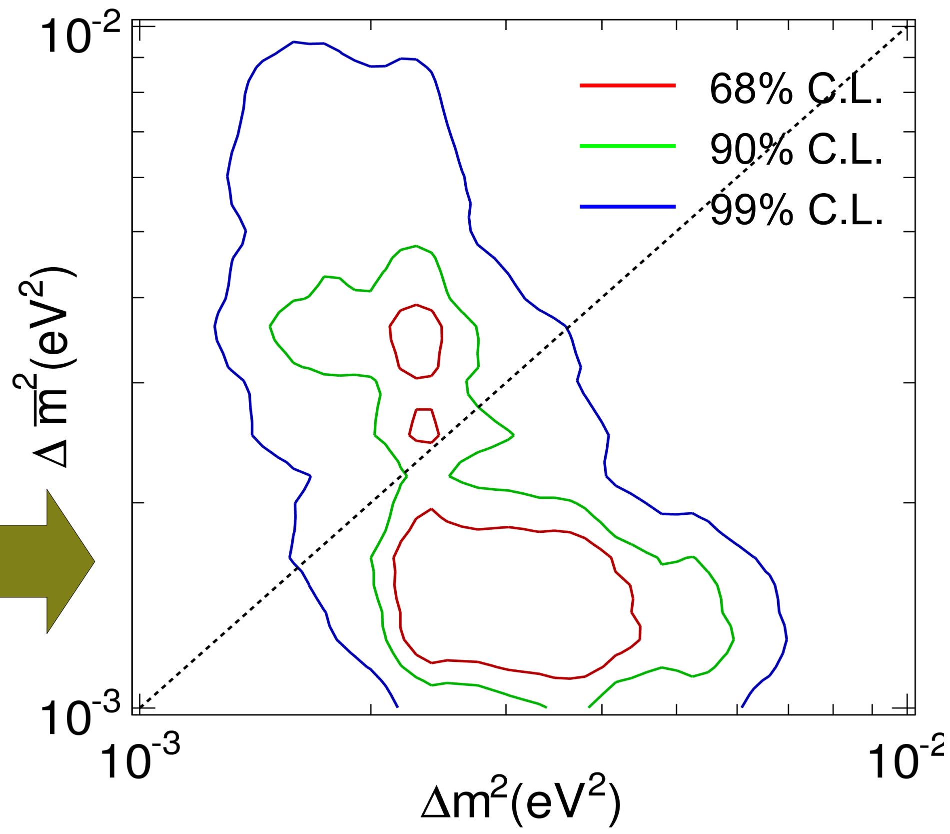
- $\Delta\phi=0$: $c^{TT}<1.2\times10^{-24}$ at 90% C.L.
  - $\sin 2\theta_v=-0.12$; $c^{TT}=0.05\times10^{-23}$
- $\Delta\phi=\pi$: $c^{TT}<1.3\times10^{-24}$ at 90% C.L.
  - $\sin 2\theta_v=-0.02$; $c^{TT}=0.06\times10^{-23}$

- Limits from other experiments
  - Cosmic ray spectrum: $\sim10^{-15}(\gamma)$, $\sim10^{-23}(p)$
  - Nuclear magnetic resonance frequencies: $\sim10^{-21}(e)$, $\sim10^{-30}(n)$

An *ad hoc* CPT Violation Test

$$P_{\nu_\mu \to \nu_\mu / \bar{\nu}_\mu \to \bar{\nu}_\mu} = 1 - \sin^2 2\theta \sin^2\left(\frac{(\Delta m^2 / \Delta \bar{m}^2) L}{4E}\right)$$

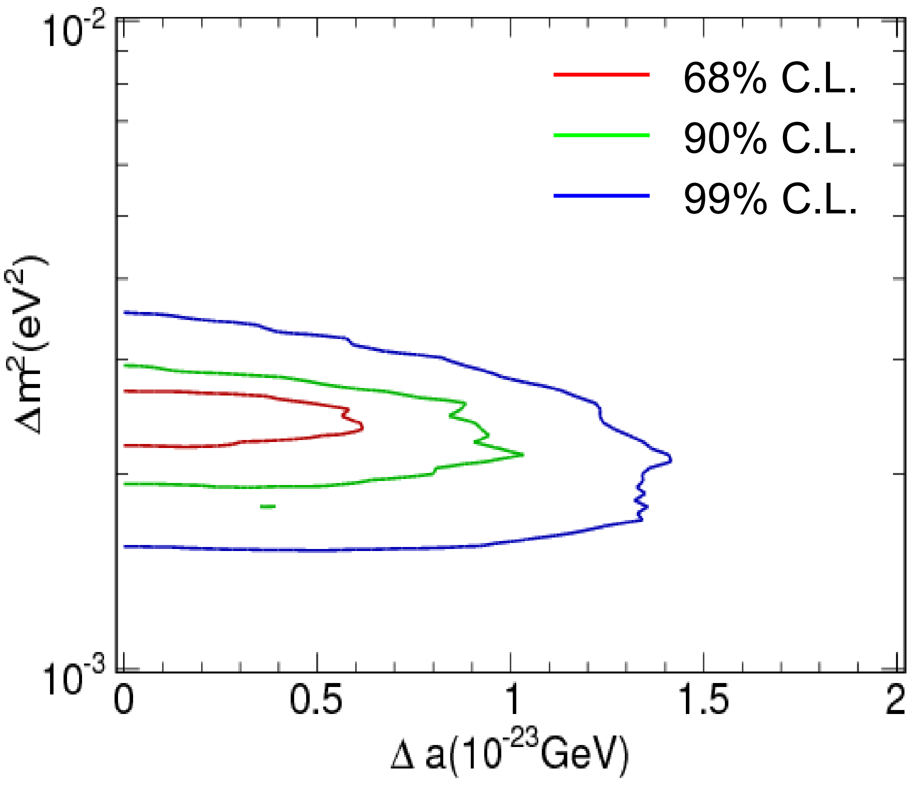
- Simple assumption: neutrinos and antineutrinos could have different mass squared splittings
  - Mainly triggered by the LSND
- Question: Is this allowed by SK?
  - Assuming maximal mixing
  - Allowing neutrinos and antineutrinos mass squared splittings change independently
- Best-fit: $\begin{cases} \sin 2\theta = 1 \\ \Delta m^2 = 3.7\times 10^{-3}\, eV^2 \\ \Delta \bar{m}^2 = 1.5\times 10^{-3}\, eV^2 \end{cases}$



Super-K best-fit is far away from the LSND scale
→ then, what is energy level CPTV effects could appear?

Limit on CPT Violation Scale

- $-a_{AB} L_A \gamma^0 L_B \Rightarrow \Delta a L$ oscillation
- As a sub-dominant effect $\Rightarrow P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4E} \pm \Delta a) L$
- Assuming maximal mixing for the mass eigenstates



- At 90% C.L.: $\Delta a < 1.05 \times 10^{-23}$ GeV

- Limits from other experiments

  Barger *et al*, PRL 85(5055), 2000

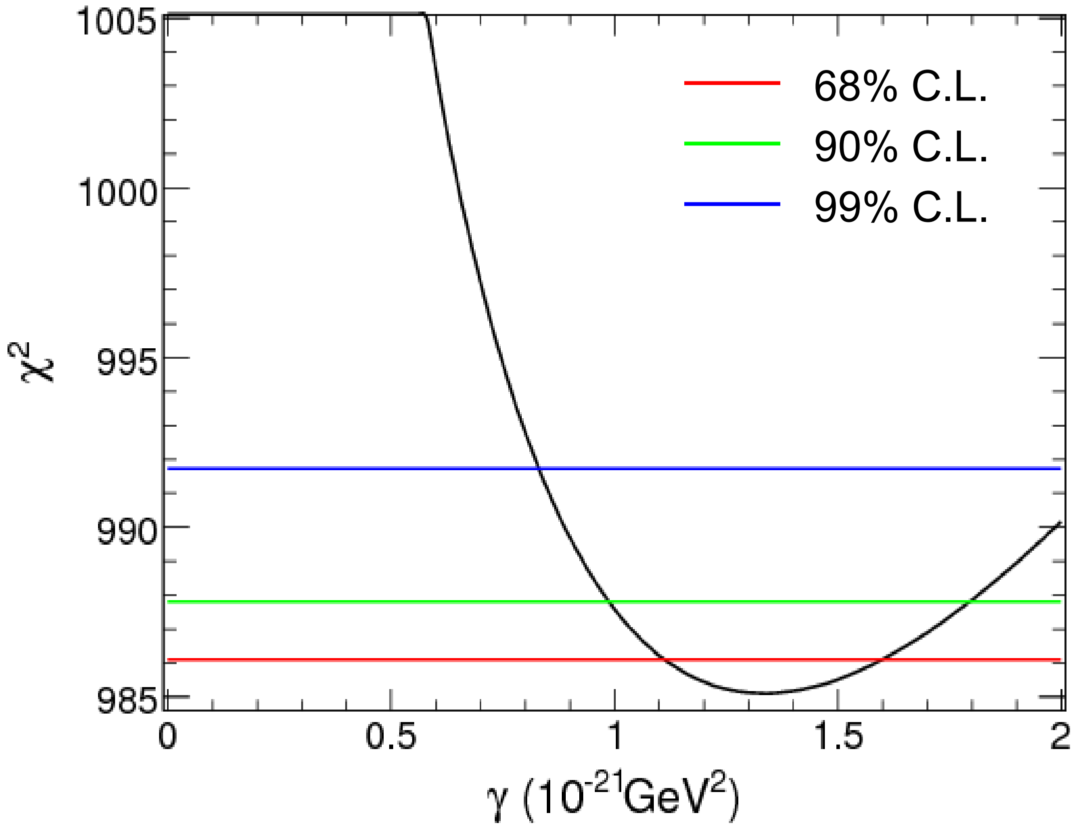
  - *g-2*: ~10^{-23} GeV
  - $K^0 - \bar{K}^0$: $\sim 0.44 \times 10^{-18}$ GeV

How Can Neutrinos Simply Vanish?

- Neutrino decoherence
  - Quantum systems can go out of coherence by interacting with the environment → "disappearance" of coherent quantum states (e.g. quantum gravity effect)
  - $P_{\nu_\mu \to \nu_\mu} = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - e^{-\gamma L} \cos\frac{\Delta m^2 L}{2E}\right)^2$
    - γ may have energy dependence: $\gamma = \gamma_0 (E/\mathrm{GeV})^n$
    - Pure decoherence (n=-1): $\Rightarrow \; P_{\nu_\mu \to \nu_\mu} = 1 - \frac{1}{2}\left(1 - e^{-\gamma L/E}\right)^2$
- Neutrino decay
  - "There is no reason to assume mass eigenstates are stable"
  - $P_{\nu_\mu \to \nu_\mu} = \sin^4\theta + e^{-\alpha L/E}\cos^4\theta + 2\sin^2\theta\cos^2\theta\, e^{-\alpha L/2E}\cos\frac{\Delta m^2 L}{2E}$
    - Pure decay case : $\Delta m^2 \to 0 \;\Rightarrow\; P_{osc} = (\sin^2\theta + e^{-\alpha L/2E}\cos^2\theta)^2$

Model Comparison: Decoherence

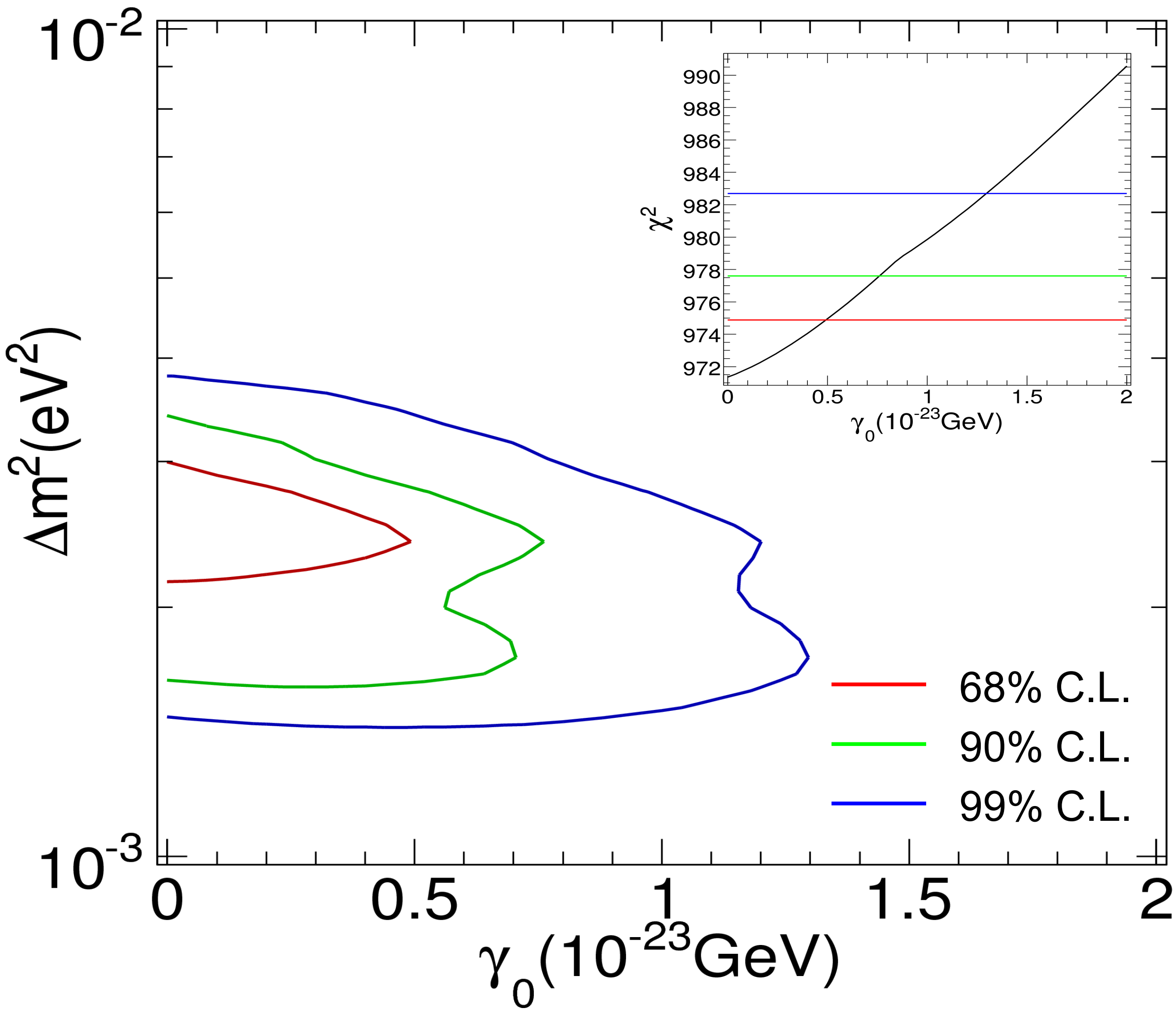
$$P_{\nu_\mu \to \nu_\mu} = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - e^{-\gamma L/E}\right)^2$$



- Best fit
  - $\gamma = 1.3\times10^{-21}\mathrm{GeV}^2$
  - $\sin^2 2\theta = 1$
  - χ^2/dof=987/853
- $\Delta\chi^2 = 16$
  $\Rightarrow 4\sigma$ exclusion level
- Neutrino decoherence does not explain SK atmospheric neutrino observation as well as the ν_μ-ν_τ oscillation

Limits on Decoherence Parameter (I)

$$P_{\nu_\mu \to \nu_\mu} = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - e^{-\gamma_0 L} \cos \frac{\Delta m^2 L}{2E}\right)^2$$

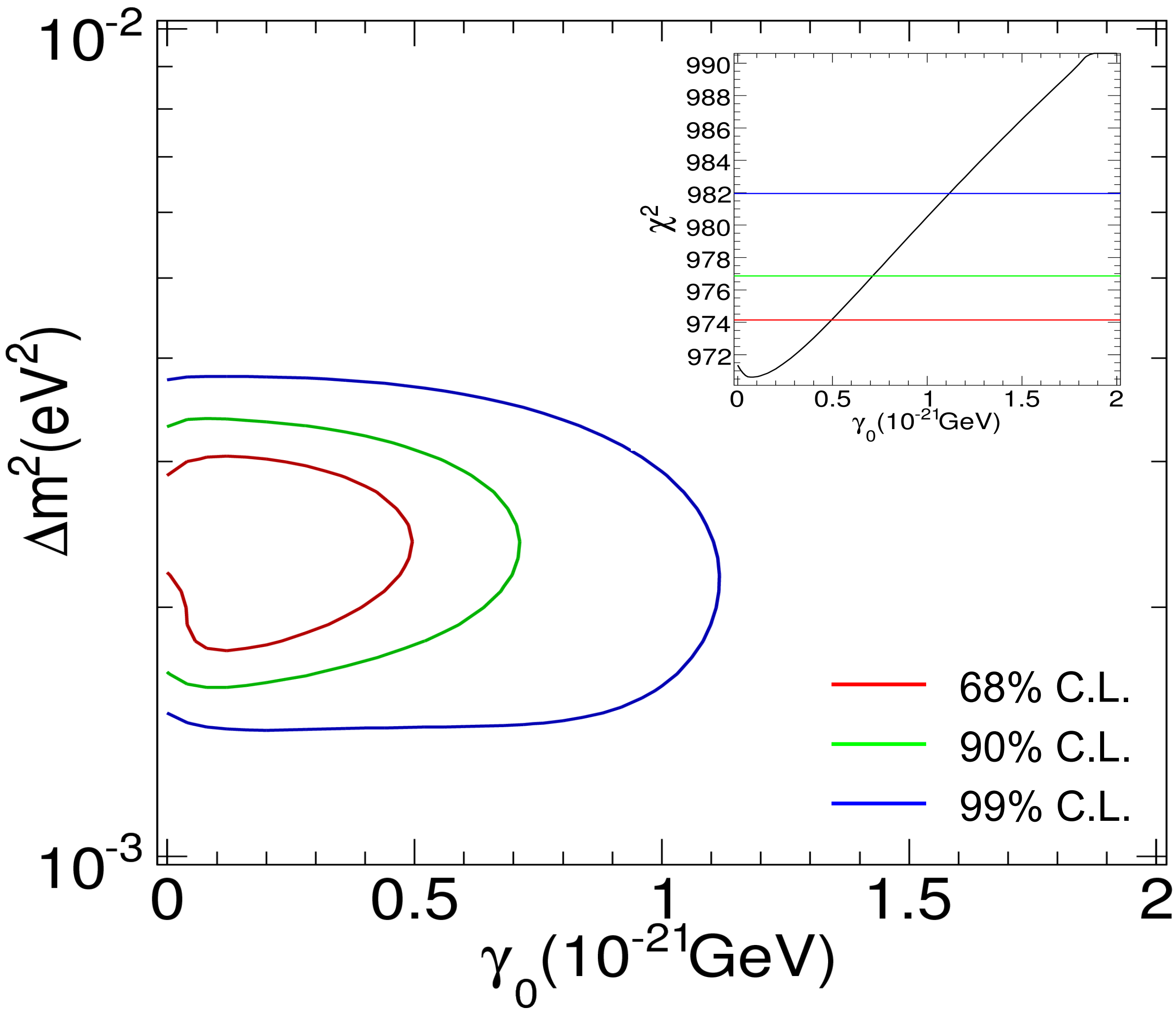


- $\gamma=\gamma_0$: most trivial case
- Best fit
  - $\gamma_0=0.$
  - $\sin^2 2\theta=1$
  - $\Delta m^2=2.4\times10^{-3}eV^2$
  - $\chi^2/dof=971/853$

At 90% C.L., the allowed limit: $\gamma_0<0.76\times10^{-23}GeV$

Limits on Decoherence Parameter (II)

$$P_{\nu_\mu \to \nu_\mu} = 1 - \frac{1}{2}\sin^2 2\theta\left(1 - e^{-\gamma_0 L/(E/GeV)}\cos\frac{\Delta m^2 L}{2E}\right)^2$$

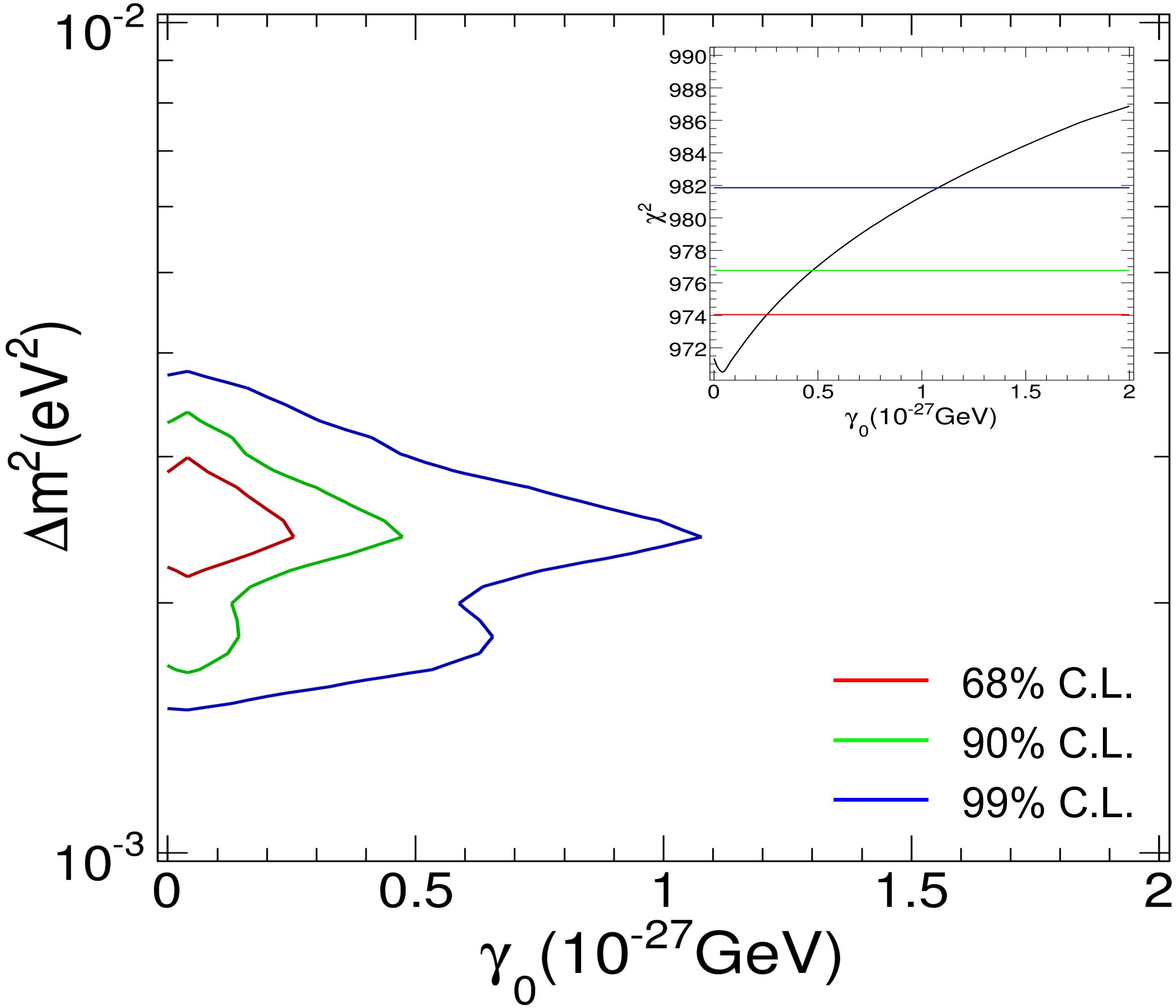


- $\gamma = \gamma_0/(E/\mathrm{GeV})$
- Best fit
  - $\gamma_0 = 0.08 \times 10^{-21}$ GeV
  - $\sin^2 2\theta = 1$
  - $\Delta m^2 = 2.4 \times 10^{-3}\,\mathrm{eV}^2$
  - $\chi^2/\mathrm{dof} = 971/853$

At 90% C.L., the allowed limit: $\gamma_0 < 0.61 \times 10^{-21}$ GeV

Limits on Decoherence Parameter (III)

$$P_{\nu_\mu \to \nu_\mu} = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - e^{-\gamma_0 L/(E/GeV)^2} \cos\frac{\Delta m^2 L}{2E}\right)^2$$

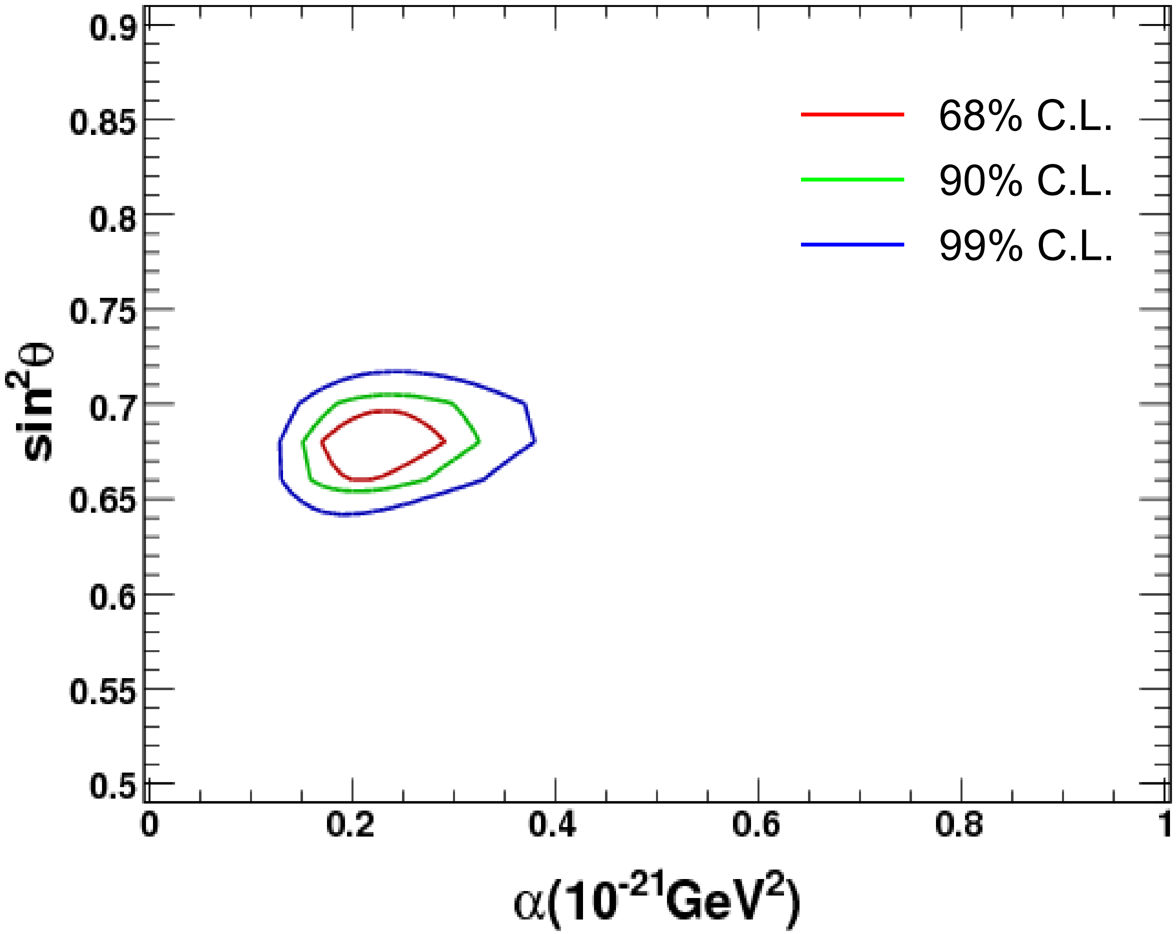


- $\gamma=\gamma_0(E/\mathrm{GeV})^2$
- Best fit
  - $\gamma_0=0.04\times10^{-27}$GeV
  - $\sin^2 2\theta=1$
  - $\Delta m^2=2.4\times10^{-3}\mathrm{eV}^2$
  - $\chi^2/\mathrm{dof}=971/853$

At 90% C.L., the allowed limit: $\gamma_0<4.8\times10^{-28}$GeV

Model Comparison: Neutrino Decay

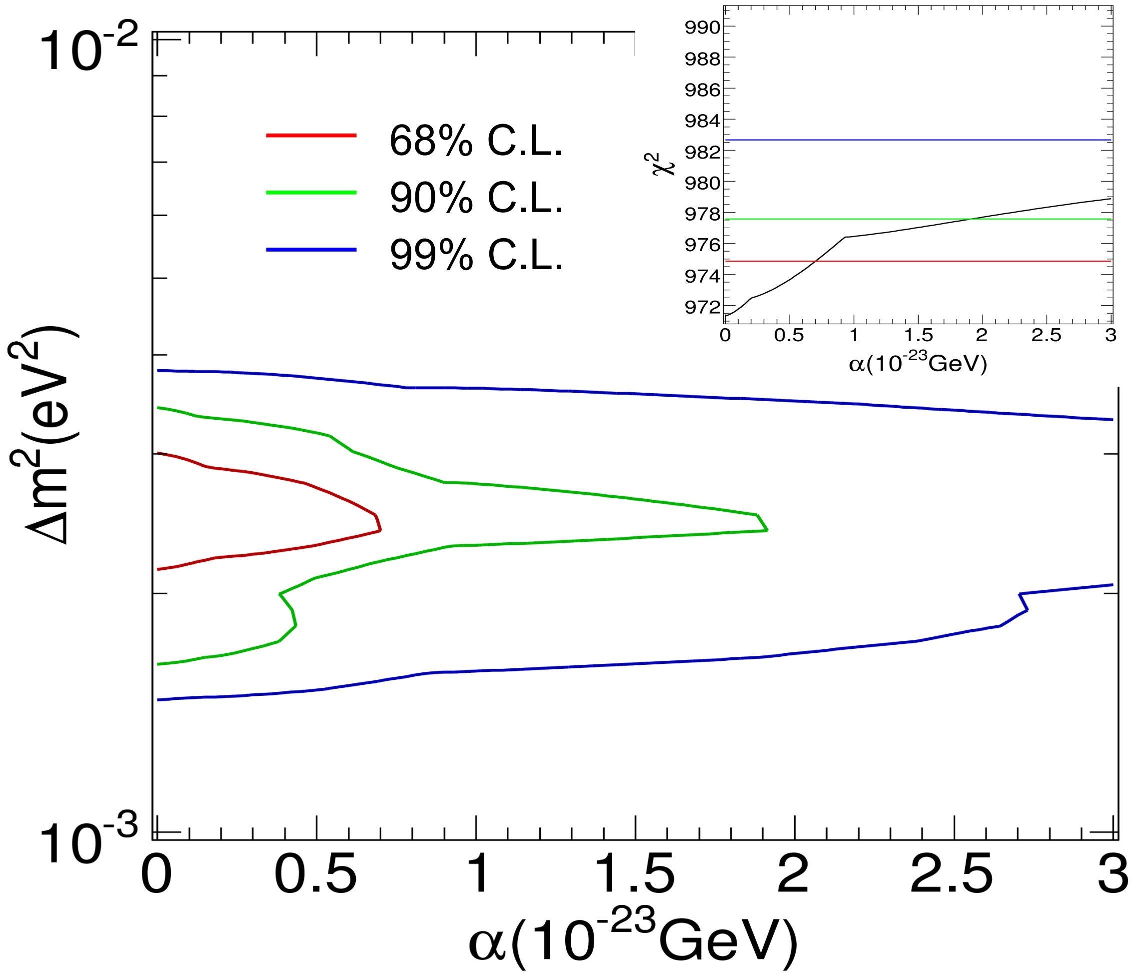
$$P_{\nu_\mu \to \nu_\mu} = 1 - (\sin^2\theta + e^{-\alpha L/2E}\cos^2\theta)^2$$



- Best fit
  - $\sin^2\theta = 0.68$
  - $\alpha = 2.2 \times 10^{-22}\mathrm{GeV}^2$
  - χ^2/dof$=983/853$
- $\Delta\chi^2 = 12$
  $\Rightarrow 3.5\sigma$ exclusion level
- Neutrino decay does not explain SK atmospheric neutrino observation as well as the ν_μ-ν_τ osc.

Limits on Neutrino Decay Parameter

$$P_{\nu_\mu \to \nu_\mu} = \sin^4\theta + e^{-\alpha L/E}\cos^4\theta + 2\sin^2\theta\cos^2\theta\, e^{-\alpha L/2E}\cos\frac{\Delta m^2 L}{2E}$$



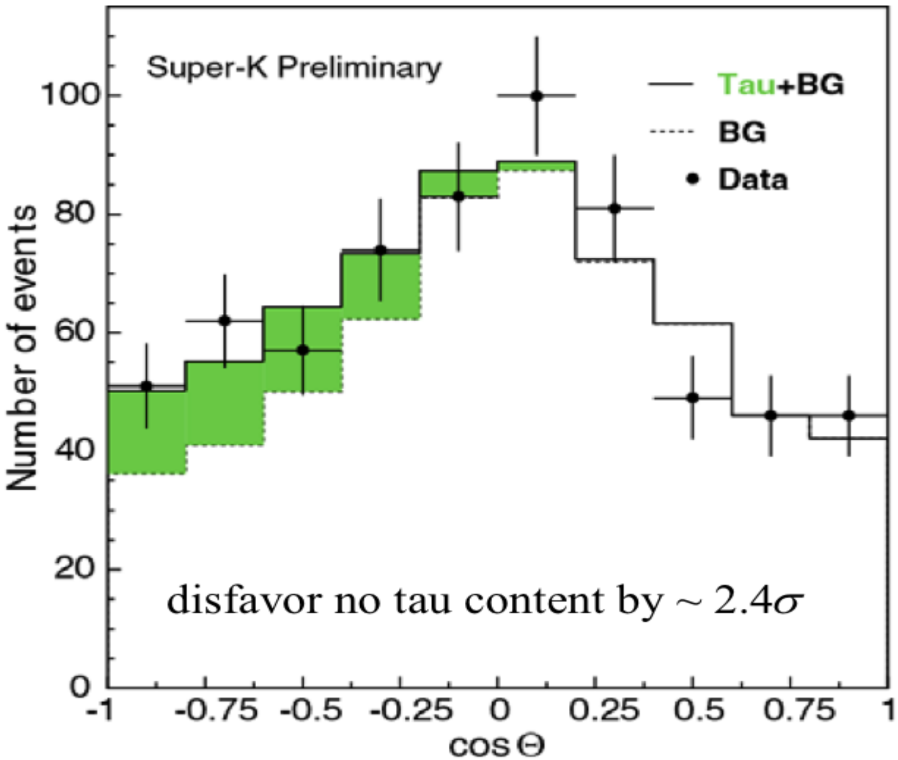
- Best fit
  - $\alpha=0$
  - $\sin^2\theta=0.45$
  - $\Delta m^2=2.4\times10^{-3}eV^2$
  - $\chi^2/dof=971/853$

At 90% C.L., the allowed limit: $\alpha<1.9\times10^{-23}GeV^2$

Summary and Conclusions

- ν_μ-ν_τ oscillation analysis is carried out using SK-I+II atm ν data
  - $\sin^2 2\theta > 0.95$, $2.2\times10^{-3}\mathrm{eV}^2 < \Delta m^2 < 2.7\times10^{-3}\mathrm{eV}^2$
- ν_μ-ν_τ oscillation is compared with 3 kinds of alternatives:
  - ν_μ-ν_s oscillation: excluded at 7.2σ
  - Oscillation induced by LIV and CPTV are excluded
  - Neutrino decoherence and decay: excluded at 4σ and 3.5σ
- Atmospheric neutrino data can provide valuable constraints on scales of new physics beyond the Standard Model
  - An admixture 23% of ν_s is allowed at 90% C.L. (2+2 mass hierarchy)
  - LIV and CPTV limits are set: $\sim10^{-24}$ and $\sim10^{-23}$ GeV at 90% C.L.
  - Neutrino decoherence limits: $\sim10^{-24}$GeV, $\sim10^{-22}$GeV, and $\sim10^{-28}$GeV respectively for different energy dependence at 90% C.L.
  - Neutrino decay limit: $\sim10^{-23}$ GeV^2 at 90% C.L.

Tau Event Searching



Statistically separate (NN & likelihood) tau-like events in high energy sample; look for up-down asymmetry (after accounting for oscillation)

- Expected: 79±28(sys)
- Found:
  - Likelihood: 145±48(stat)+15/-38(sys)
  - Neural Network: 152±47(stat)+17/-29(sys)

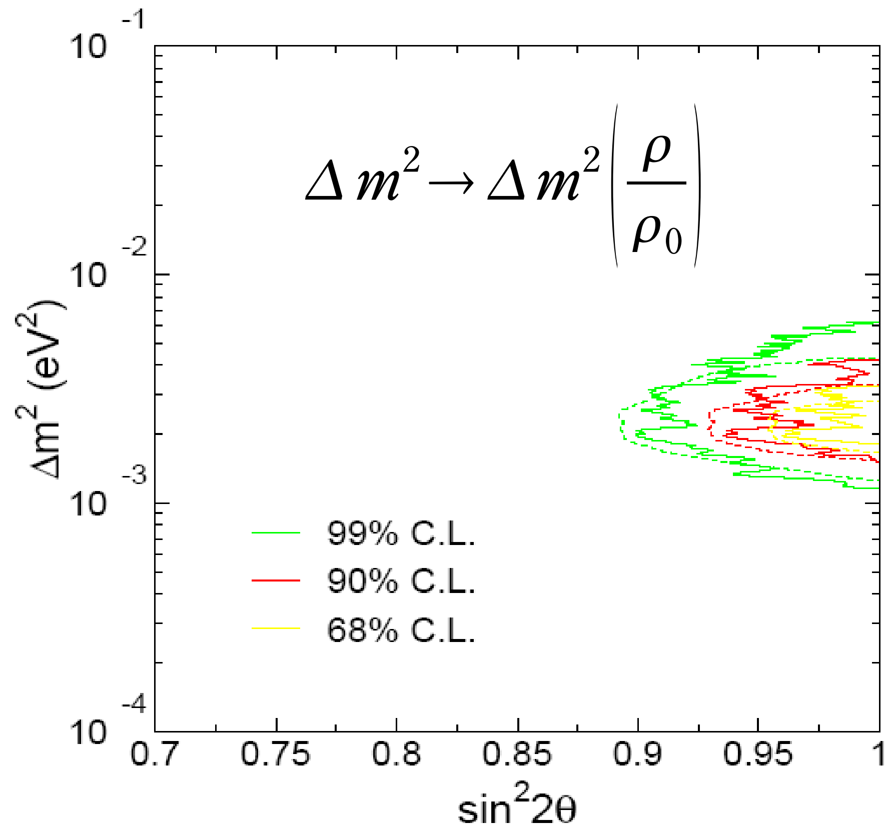
No tau events assumption is disfavored by $\sim 2.4\sigma$

Testing MaVaN

- Neutrinos gain mass only in high density matter (not in air or vacuun

- Best Fit:
  - χ^2_{MaVaN} = 194.4/178 d.o.f
    ($\sin^2 2\theta$, Δm^2) = (1.00, 2.19×10^{-3} eV^2)
  - $\chi^2_{\mathrm{Standard}}$ = 174.97/178 d.o.f
    ($\sin^2 2\theta$, Δm^2) = (1.00, 2.11×10^{-3} eV^2)

- Excluded at 4.4σ level



------- Standard 2-flavor oscillations

——— MaVaN oscillations

Next step: $\Delta m^2 \rightarrow \Delta m^2 \left(\frac{\rho}{\rho_0} \right)^n$